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# MEASUREMENT OF ICE/PROPELLER INTERACTION PARAMETERS - MV ROBERT LEMEUR ENGINEERING & FIELD TESTS

PREPARED FOR THE TRANSPORTATION
DEVELOPMENT CENTRE

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CANADIAN MARINE DRILLING LTD.
CALGARY, ALBERTA
AUGUST, 1985

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The Contractors assume no responsibility for any subsequent use of the information contained in this report.

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17. Abstract

The starboard shaft of the M.V. Robert LeMeur icebreaking supply ship was instrumented for the purpose of measuring ice/propeller interaction forces. The vessel is a twin screw controllable pitch propeller (CPP), nozzled vessel with 3500 kW per shaftline. Major components instrumented were: Propeller blade; CPP yoke pin: CPP actuating oil pressure; shaft torque and thrust; engine parameters; ship speed, and lateral shaft movement. Design, installation and calibration of these elements are described. A digital data selection and acquisition system together with a near-real-time data analysis system were designed and constructed for the project.

A field test program was executed in June/July 1984 in the seasonal ice of the Canadian Beaufort Sea adjacent to Tuktoyaktuk, N.W.T. Data was successfully collected from all installed systems and environmental ice conditions were monitored and documented.

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17. Résumé

Le mesurage des forces d'interaction en jeu a été rendu possible par l'instrumentation de l'arbre porte-hélice tribord du Robert-LeMeur, cargo brise-glace à deux hélices à pas variable sous tuyère, développant 3,500 kW par arbre. Les organes ou les paramètres concernés par le mesurage ont été les suivants: la pale de l'hélice, la goupille d'accouplement, la pression d'huile dans les circuits de commande du pas d'hélice, le couple de torsion et la poussée sur l'arbre, les paramètres moteur, la vitesse du navire et les déplacements transversaux de l'arbre. Le rapport décrit la réalisation, l'installation et l'étalonnage de ces organes ainsi que la chaîne de mesure conçue exprès pour la saisie, la sélection et la numérisation des données suivie de l'analyse en temps quasi réel de l'information traitée.

De juin à juillet 1984, des essais ont été effectués dans la mer de Beaufort recouverte de glace saisonnière, au large de Tuktoyaktuk dans les Territoires du Nord-Ouest. Tous les systèmes ont bien fonctionné et des observations sur les types de glaces rencontrées ont été faites et dûment consignées.

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# SUMMARY

The designers, operators and regulatory bodies for Arctic shipping, have had a long standing interest in the strength and reliability of propulsion systems. Strength aspects of the vessels' propellers themselves have become particularly critical as vessels operate in more severe ice conditions. Failure of the propeller blades has been a common experience for these ice transiting vessels.

Since the early 1970's there has been an increasing number of icebreaking vessels equipped with constant speed controllable pitch propellers (CPP) rather than variable speed drives and fixed pitch propellers (FPP). The CPP units have had mixed success with some major failures and some real advantages. In an attempt to reduce the ice generated forces on the propellers and internals of the hub, some vessels have been designed with the shrouded propellers.

The main justification for measuring ice interaction forces in a ducted propeller, was the lack of full scale data. Thus, design would have to have been based on other sources, e.g. blade failures of open propellers, or extrapolation from open water designs. The data from a full scale measurement project would ultimately enable the design of propellers for ice-going vessels to be put on a firm engineering and scientific base and applicable regulations and rules could likewise be based on a further understanding of the processes occurring during ice/propeller interaction.

This report covers the preparatory engineering, the field test program itself and the analytical modelling work on the ice propeller interaction and propulsion system response in support of a full scale test program to measure ice propeller interaction forces. Analysis of collected data is not included in this report and will be covered in the remaining reports of this project.

This project arose out of a previous study "The MV Robert LeMeur Nozzle Propeller Ice Force Measurement Project - 1983 Final Report", Transportation Development Centre, Transport Canada Report NO.: TP5685E, executed by Canmar. Note that this report has restricted access until January 1987. The 1983 project had only partial success in that significant failures in the propeller blade instrumentation precluded the accurate determination of

ice induced propeller blade loads and load locations. The data obtained, however, proved to be of value, and indicated that the general approach was sound. The current project was initiated with an expanded scope relative to the 1983 test program. The additional major elements were: The measurement of forces on the yoke pin sliding block; The measurement of shaft movement due to ice/propeller interaction; The collection of ice/propeller interaction statistics over one operating season; The generation of simple analytical models, and; The provision of a high level of onboard data inspections and analysis capability. The original aims of the 1983 program, namely to measure the magnitude and locations of ice induced propeller blade loads and to analyse such collected data, are also included in the current scope of work. Particular attention was paid to the failures experienced in the 1983 test program so that improved methods and procedures could be incorporated, as appropriate, in the 1984 test program.

The analytical modelling covered the ice/propeller interaction phenomena, the response of the blade to dynamic and static loads, the transfer function between the applied load and the yoke pin, and the longitudinal and torsional response of the propeller shafting to ice induced loads.

The intent of the analytical work on ice/propeller interaction was to generate an understanding and expressions of the phenomena occurring in a nozzle. Formulas derived explicitly for shrouded propellers may not be appropriate for unshrouded propellers due to the different loading scenarios. In the case of open screws, large loads are said to be caused by milling, in which the tip of the blade cuts or mills the ice. In the case of a nozzle, it is expected that the whole of the leading edge of the blade will be involved in this interaction rather than the blade tip. In the modelling work, estimates have also been made of the contribution of the various water forces on the propeller blade, as well as those due to mechanical ice contact.

The second aspect of the modelling was to generate a simple beam model of the propeller blade as a guide to understanding the reaction of the propeller blade to static and dynamic loads.

A simple model relating the reaction of the yoke pin to externally applied blade loads was also generated, again to be used as an aid in understanding the field data and to also investigate the effect of friction in the blade support. This was especially important since one of the motivations for measuring the yoke pin loads was to obtain data on the dynamic loads transmitted to the internals of the hub.

A final model generated was the lumped mass model of the propulsion train, designed to relate applied torques at the propeller plane to measured shaft torque readings on the intermediate shaft. A second lumped mass model was developed to relate shaft thrust measurement to thrusts applied to the propeller blades. In these models both static and dynamic responses were explicitly included. Apart from again providing necessary cross checks on the various data, they may, ultimately be able to provide information on the direction of the ice force on the propeller blade.

The majority of the analytical modelling work was performed prior to the field tests in order to further enhance the utility of the field test program.

The tests were performed using the MV Robert LeMeur, a CASPPR Class 3 icebreaking supply vessel, during June and July 1984 in the Canadian Beaufort Sea adjacent to Tuktoyaktuk, N.W.T. The vessel is equipped with two controllable pitch propellers situated in nozzles, each shaft line capable of absorbing approximately 3500 kW.

To measure ice interaction forces, one of four blades of the starboard propeller was instrumented with six strain gauge bridges. The strain gauge assembly was calibrated by applying a series of static, point loads to the blade surface and recording the strain gauge outputs. This data enabled the locations and magnitude of the applied force to be calculated using the strain gauge readings collected during ice/propeller interaction. A yoke pin sliding block was also instrumented with strain gauges in order to measure the forces applied to the yoke pin as a result of ice/propeller interactions. This assembly was calibrated using a hydraulic press. The intermediate propeller shaft was instrumented as before to measure shaft torque and thrust. A pressure transducer was installed in the oil-distribution box of the starboard shaft line in order to measure pitch actuation pressures and transients. Subsidiary parameters such as engine fuel rack position, shaft speed, propeller pitch angle, rudder angle and ship speed were also recorded by utilizing previously installed research instrumentation. Four magnetic proximity probes were installed in the stern tube bearing to monitor the location of the tail shaft relative to the bearing surface and hence to study the lateral movement due to ice/propeller interactions.

In order to enhance the performance of the field test program and the quality of the data, computer based data acquisition and analysis systems was developed. The data acquisition system had the capability to capture 6.81 second segments of data positioned around significant ice/propeller interaction events. Specifically designed circuitry allowed the on-line identification of significant events so that they could be permanently stored. Each data file contained 7000 readings on each of 18 input data channels. The sampling rate was approximately 1000 readings per channel per second.

The digital event detection and subsequent storage was a departure from the more common approach of recording all data on analogue media. Our approach was to identify, before the construction phase of the project, the desired class of events using all available data and then to record those desired events in the field at high precision and resolution. Thus, post-test time can be spent on interpreting and analyzing the significant data rather than spending much time searching the data set. The digital data approach was also essential in the provision of onboard data analysis capability.

The data analysis system provided the capability to view the acquired data and to perform preliminary analysis of the data while the collection of new data was on-going. Analysis capability included display of acquired data, estimation of ice interaction forces from the propeller blade strain data, Fourier Transforms and digital filtering of acquired data. The shaft movement data could be processed to display the relative position in a convenient X-Y plot format.

The field test program resulted in the collection of 343 events (which were stored on floppy disk) during both open water and ice breaking operations. Ice conditions during the tests were monitored and analysed and are reported here.

LIST OF SYMBOLS

$A_\otimes$ = cross sectional area of ice block [$m^2$]

$A_{prop}$ = area of propeller disc. $A = \pi D^2/4$ [$m^2$]

BAF = blade axial force [N]

BBM = blade bending moment [Nm]

BM(r) = bending moment at section r [Nm]

BRF = blade radial force [N]

BSF = blade shear force [N]

$c_o$ = speed of sound waves in ice [m/s]

$c_R$ = drag coefficient [-]

$c_T$ = propeller loading coefficient [-]

D = propeller diameter [m]

E = elastic modulus of ice [Pa]

F = force, general [N]
Fx, Fy, Fx components of the force in x, y, z directions

H = depth of the blade below the water surface (immersion) [m]

DHP = delivered horsepower [HP]

I = inertia of blade section [$m^4$]

$J_G$ = polar moment of inertia about the centre of gravity [kg $m^2$]

$K_{ic}$ = critical stress intensity factor [$kN/m^{3/2}$]

KE = kinetic energy [N.m] or [J]

L = effective length of an ice block [m]

M(n) = added mass for nth mode [kg]

Mi = added mass [kg]

N = number of blade impacts during a milling event [-]

$p_p$ = pressure on blade's pressure side [Pa]

$p_s$ = pressure on blade's suction side [Pa]

R = radius of propeller blade tip [m]

R = water drag [N]

$R_o$ = inside radius of the nozzle ring [m]

$R, R_x, R_y, R_z$ = coordinates of the point of force application with reference to fixed coordinate system [m]

$s_{axial}/s_{circum}$ = axial and circumferential advancement of the blade [m]

SM = section modulus of blade section [$m^3$]

$T_{id.prop}$ = thrust of ideal propeller [N]

$T_{max}$ = impact duration [s]

$T_{mill}$ = duration of milling event [s]

$V_1, V_2$ = velocity of water at point 1 and 2 in the liquid

$V_{L.E.}$ ; $V_{S.S.}$ ; $V_{P.S.}$ = velocities of advancement of the blades leading edge, suction sides and pressure side respectively, taken in the direction normal to the surface [m/s] [m/s]

$V_{ax}$ = axial velocity of water in propeller disk plane [m/s]

$V_{crack}$ = velocity of crack propagation [m/s]

$V_{mp}$ = water axial velocity in propeller disk plane [m/s]

$V_{tot}$ = total water inflow velocity [m/s]

$V_u$ = circumferential velocity of water induced by the propeller rotation [m/s]

$V_o$ = initial velocity [m/s]

$X_A, \ddot{X}_A$ = linear advancement and acceleration of ice piece at point A [m],

Z = number of blades [$m/s^2$]

a = acceleration [$m/s^2$]

b = width of ice block [m]

cos x, cos y, cos z = cosine directional of force vector

d = spacing between blades measured circumferentially [m]

e = eccentricity of collision [m]

$f_{ni}$ = frequency of $i^{th}$ mode [Hz]

$g$ = acceleration due to gravity [m/s$^2$]

$h$ = ice block thickness [m]

$h_z$, $h_{tip}$ = thickness of the blade section at root and tip, respectively [m]

$k$ = spring constant [N/m]

$l_{crack}$ = length of the crack [m]

$m$ = mass [kg]

$n$ = rate of revolutions [1/s]

$p$ = pressure/specific strain energy [Pa]

$r$ = radius of propeller section [m]

$r_o$ = radius of propeller hub [m]

$s$ = axial advance of the blade in fixed coordinate system [m]

$t$ = time, general [s]

$t_{(blade)}$ = time to turn the blade [s]

$t_{crack}$ = time to propagate the crack [s]

$v$ = velocity [m/s]

$x$ = penetration of blade into ice [m]

$x_G$ = abscissa of the center of gravity of ice block [m]

$\sigma_{crush}$ = specific crushing energy/crushing strength [Pa]

$\sigma_{tens}$ = tensile strength of ice [Pa]

$\alpha_i$ = angle of the advancement of the blade [°]

$\theta_r$ = pitch angle at radius r [°]

$\alpha_r$ = blade advance angle at radius r [°]

$\alpha_E$ = effective blade advance angle [°]

$\ell$ = thickness of ice piece being shaven-off [m]

$\rho$ = water density [kg/m$^3$]

$\rho_i$ = ice density [kg/m$^3$]

$\omega$ = angular velocity of the blade [rad/s]

$v_r$ = linear velocity of the blade in circumferential direction

$\Delta p$ = pressure difference between two points in a liquid [Pa]

$\rho_B$ = mass density of a submerged body [kg/m$^3$]

$\nu$ = kinematic viscosity of water [m$^2$/s]

$\gamma$ = specific gravity of water [N/m$^3$]

$\lambda$ = added mass coefficient

$\omega$ = circular frequency of a simple harmonic oscillator [rad/s]

$\dot{x}_G$, $\ddot{x}_G$ = velocity and acceleration of the centre of gravity of ice block. [m/s], [m/s$^2$]

$\tau_{crack}$ = crack initiation stress [Pa]

$\nabla$ = volume of crushed ice [m$^3$]

$\psi$ = difference of pitch angle [°]

$\sigma_m$ = stress due to bending moment [Pa]

$\sigma_s$ = shear stress [Pa]

$\delta_{tip}$ = deflection of the tip of the blade [m]

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THE INSTRUMENTED PROPELLER
OF THE M.V. ROBERT LEMEUR IN DRYDOCK

# 1. INTRODUCTION

## 1.1 Background

To the designers, operators and regulatory bodies of vessels navigating in ice covered waters, the strength and reliability of the propulsion system has been a topic of longstanding concern. According to Wind (Reference 1.1), the first icebreaker was constructed in 1850 and was ineffective due to the vulnerability of its paddle wheels. The first screw driven icebreaker, the Yermak, was built in the last century in the United Kingdom for Russia. From that time until the mid-1970's, large icebreakers used fixed pitch propellers with variable shaft speed in order to change the direction and magnitude of the developed thrust.

In 1971, the exclusive use of the simple fixed pitch systems came to an end with the inclusion of an open screw, controllable pitch propeller (CPP) in the design for the United States Coast Guard's, Polar Sea Class of icebreakers. The Polar Star first entered service in 1976 and within a few days of Arctic service, had suffered significant failures of the hub internals (Ref 1.2). These problems raised the question of whether CPP systems were inherently unsuitable for ice service or whether this was just an unsuccessful implementation of the concept. To put the question into perspective, fixed pitch propellers have also had a long and regular history of blade failures (Ref 1.1), and in some cases, blade failure is considered a normal part of the operation of the vessel.

An alternative design approach was to place the CPP mechanism within a nozzle, thereby limiting the size of ice blocks impacting the blade. Since for open screw CPP mechanisms, the most severe impact loads appeared to be from massive blocks of ice causing out-of-plane loads in the blades, limiting the block size might be expected to limit the interaction force. On the other hand, there is the concern that the presence of the nozzle could promote ice milling causing the nozzle itself to become blocked. These aspects would reduce the net thrust that the propulsion system could develop and generally cause transient loads within the whole drive train.

If it is assumed that the interaction forces are limited by the presence of a nozzle, propeller blades may be made thinner and the hub/diameter ratio smaller, thereby increasing the hydrodynamic efficiency of the system, compared to the case of an open screw CPP system (Ref 1.1).

Data for estimating ice loads has for the design and specification of nozzled CPP systems, has previously been obtained from a number of sources, the major ones being:

- Classification Society Rules,
- Extrapolation from ice-free designs,
- Finite Element modelling of the interaction process,
- Model scale tests,
- Torque and thrust measurements from the propeller shaft in full scale, and
- Data on failures.

The major data source, absent for nozzled CPP systems, is full scale propeller/ice load data from vessels during normal ice-breaking operations.

## 1.2 History Of The Project

The concept for the project was created in June, 1981, when it was decided by Canmar to instrument a propeller blade of the MV Robert LeMeur with a view to determining blade bending moments, blade spindle torques, load magnitudes and locations caused by ice/propeller interactions. The MV Robert LeMeur was a particularly suitable vessel as it, at that time, was in the early stages of construction. Thus, the modifications required for a research project could easily be made to the vessel. An additional advantage was gained from the fact that the vessel not only was designed by Canmar staff, but that it would also be operated by Canmar in its northern fleet.

The MV Robert LeMeur is an icebreaking supply vessel, rated as CASPPR Class 3. It is equipped with twin screws, each 3.0 m diameter, type KA.60, in modified NSMB #37 nozzles, absorbing 3500 kW, to give an estimated total bollard pull of 103 tonnes. Reference 1.3 contains very useful background material on the design of the MV Robert LeMeur.

The technical consulting work throughout the initial stages of the project was contracted to the Technical Research Centre of Finland Ship Laboratories because of their experience in a similar experiment on a Finnish vessel (Ref 1.4). Considerable work was required prior to the MV Robert LeMeur's departure from the Burrard Yarrows

Corporation Shipyard in Vancouver, British Columbia, in September, 1982. The major components of the technical work were the design of the measurement system, the instrumentation and calibration of the propeller blade, its mounting on the hub and the installation of instrumentation cabling in the propeller shafting. Additional work at this stage was related to installation of instrumentation onboard the vessel including propeller shaft torque and thrust measurement systems and a Microwave Doppler Speed Log.

After the successful journey of the MV Robert LeMeur to the Canadian Beaufort Sea in October, 1982, the vessel played an active role in the Dome/Canmar northern operation for the remainder of the 1982 season. The vessel then over-wintered at McKinley Bay, N.W.T. and resumed operation in the spring of 1983.

The details of the joint project from its inception in 1981 until March, 1984, are covered in "The MV Robert LeMeur Nozzle Propeller Ice Force Measurement Project - 1983 Final Report", Transport Canada Report Number TP5685E (Ref 1.5).

During the preparatory phase for the field tests, some serious malfunctions were discovered in the propeller blade instrumentation. Of the six strain gauge bridges mounted on the blade, only one full bridge was found to be in working condition. Two further gauges could be made to operate in a half bridge configuration. The result was that there were insufficient strain gauge signals available to allow the location and magnitude of the ice load to be determined. However the field program was still executed because, even in the reduced configuration, valuable data could be collected.

While the data obtained during the 1983 field test program did not achieve the original aims in terms of blade loads and load locations, enough data was collected to indicate that the approach was fundamentally sound. A new project for the Transportation Development Centre was then initiated and started in early 1984 which would build upon and expand the scope of the data collection and analysis.

### 1.3 Project Objectives

There were seven major objectives for the 1984 project, all of which were related to the measurement and analysis of the various aspects of the ice/propeller interaction phenomena occurring on the MV Robert LeMeur:

- To determine from physical measurement the ice induced loads on one propeller blade.
- To determine from physical measurement the ice induced loads on the yoke pin of the CPP mechanism.
- To determine changes in the hydrodynamic lubrication condition in the stern tube bearing due to ice/propeller interaction.
- To develop digital data acquisition and analysis systems capable of near-real-time data selection and analysis.
- To record statistical data of ice induced thrust and torque transients on the intermediate propeller shaft, and to collect such data for one complete operating season.
- To analyze the data to provide a coherent picture of the ice/propeller interaction phenomena, bearing in mind the ultimate use of the data in the generation of design criteria and regulations.
- To develop simple, analytical models of the propulsion system to describe the various aspects of the ice interaction phenomena.

## 1.4 Overview

There were several major changes and additions to the scope of the 1984 test program in order to improve the likelihood of success and to increase the value of the data. The main emphasis was on the monitoring of more parameters, on improving the execution during the test phase by creating analytical models, and on the development of onboard data analysis capability. Of the project objectives listed in Section 1.3, items 2, 3, 4, 5 and 7 were new elements for this project and only items 1 and 6 had been included in the scope of the 1983 test phase.

Particular notice was paid to the instrumentation failures experienced during the 1983 project. The major failure was the loss of signals from the strain gauge installation in the propeller blade. Steps were taken to avoid a recurrence of the failures, primarily they were to collect data within one month of the vessel being put in the water. (In the 1983 project, the vessel was operational from about September 1982 until early December 1982, it then overwintered until June 1983. Data was not collected from the system until late June 1983.)

Additional precautions were taken with the protection and sealing of the gauges in the blade.

Partially as a result of the data collected during 1983, it was felt that additional parameters should be monitored during the second (1984) test program. The Polar Star, for example, experienced failures (see Ref 1.2) to the internals of the CPP mechanism rather than to the hub. Instrumentation was therefore added to measure the forces transmitted to the internals of the CPP mechanism as a result of ice induced spindle torques. Friction between the blade carrier and the hub body would be expected to reduce the effects of the ice induced torques and hence provide additional margins of safety to the hub internals. For CPP systems in nozzles, there did not appear to be any full scale data available on this aspect. The sliding block surrounding the yoke pin was instrumented so that forces on this component could be estimated.

A pressure transducer was installed, for the 1984 project, to measure the pitch actuation oil pressure. Measurements were made across the spool valve in the expectation that ice induced spindle torques and hence hub cylinder movement would generate transient pressure pulses in the oil actuation system.

In icebreakers and ice-going vessels, wear of stern tube bearings and sealings was also a topic of some concern. Therefore, magnetic proximity probes were installed in order to monitor the movement of the propeller shaft as a result of ice/propeller interactions. The advantage of performing such measurements while simultaneously recording the reaction of the blades and shafting was that a better overall understanding of the phenomena will be obtained.

When collecting data suitable for design purposes, information on both extreme loads and on possible fatigue loadings are useful. To obtain a data base for estimating fatigue of the propulsion components due to ice propeller interaction, statistical data recorders were installed on the starboard shaft line. Data on extreme values and interaction frequencies for shaft torque and shaft thrust would be collected for one operating season and correlated with ice conditions.

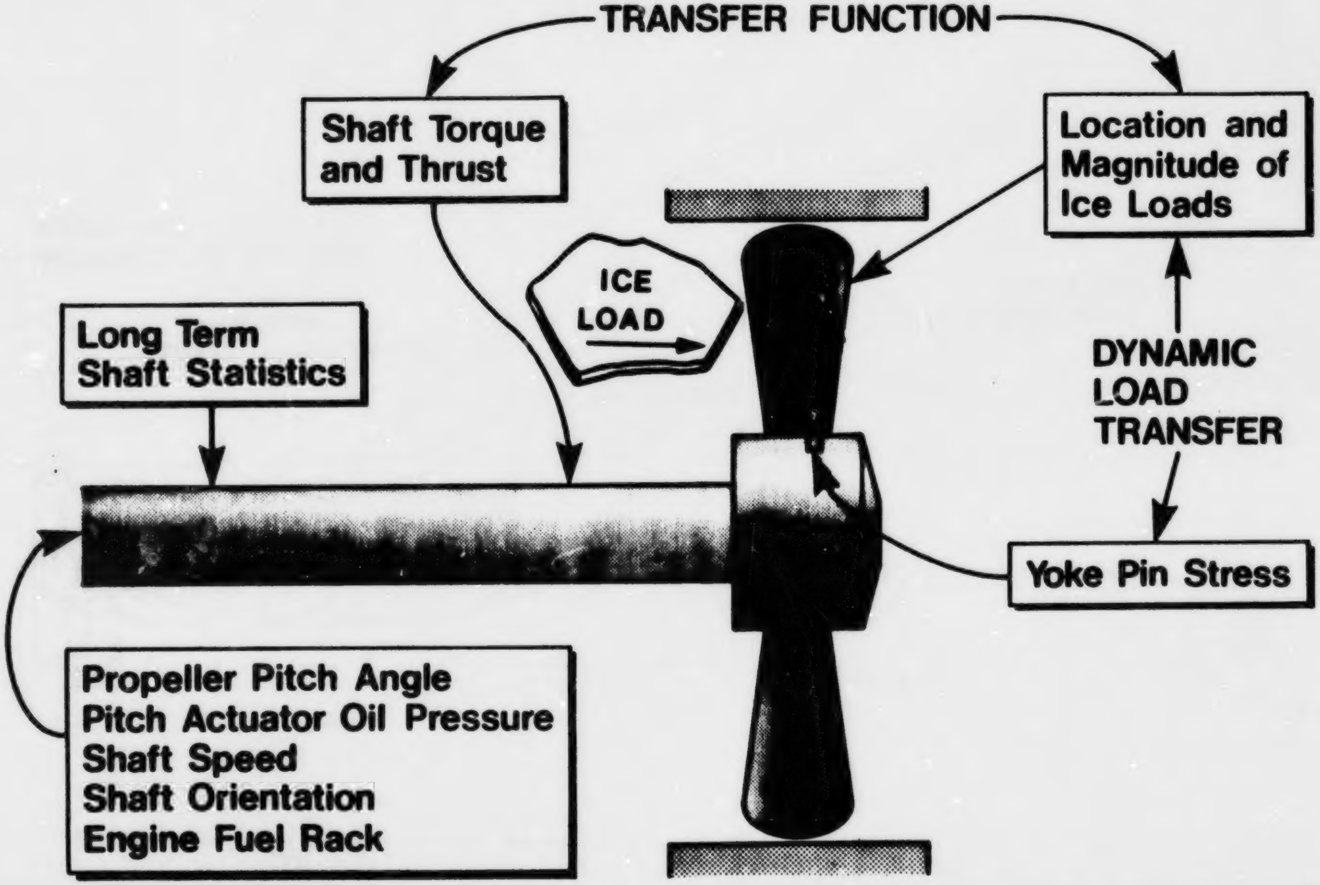
Traditionally, the approach to full scale ship testing has been to collect data on analogue multi-channel FM (Frequency Modulated) recorders, view the data via strip chart recorders and then follow with an analysis of the data after the testing program has been completed. A major disadvantage of this approach is poor on-site feedback and often poor post-test utilization of time. Time is spent replaying the data and extracting the parts of interest. The approach that was taken in this project was significantly different. Rather than record all data for the whole test period, instrumentation was developed that could, in real-time, identify the occurrence of significant ice/propeller interactions and store only the data adjacent to the event. Thus a major reduction in data requiring inspection and analysis was achieved. Secondly, a level of analytical capability was included onboard so that, at least first approximations of derived quantities of interest were available, ie. ice induced blade forces, locations, spindle torques and bending moments. As a result, during the tests the project team had the opportunity to refine or change the direction of test execution. The above approach was possible due to the valuable expertise the Canmar team had obtained over a number of years in full scale ship tests and the fact that some data had been obtained from the 1983 tests.

As a further aid to the on-site test team, work was done on developing simple analytical models to describe the ice/propeller interaction phenomena occurring in a nozzled CPP system. A simple model of the blade dynamics as well as a model to relate the yoke pin load to the applied blade load and to the system geometry were created. Lastly, a model to relate shafting response to an applied external forcing function at the propeller was developed.

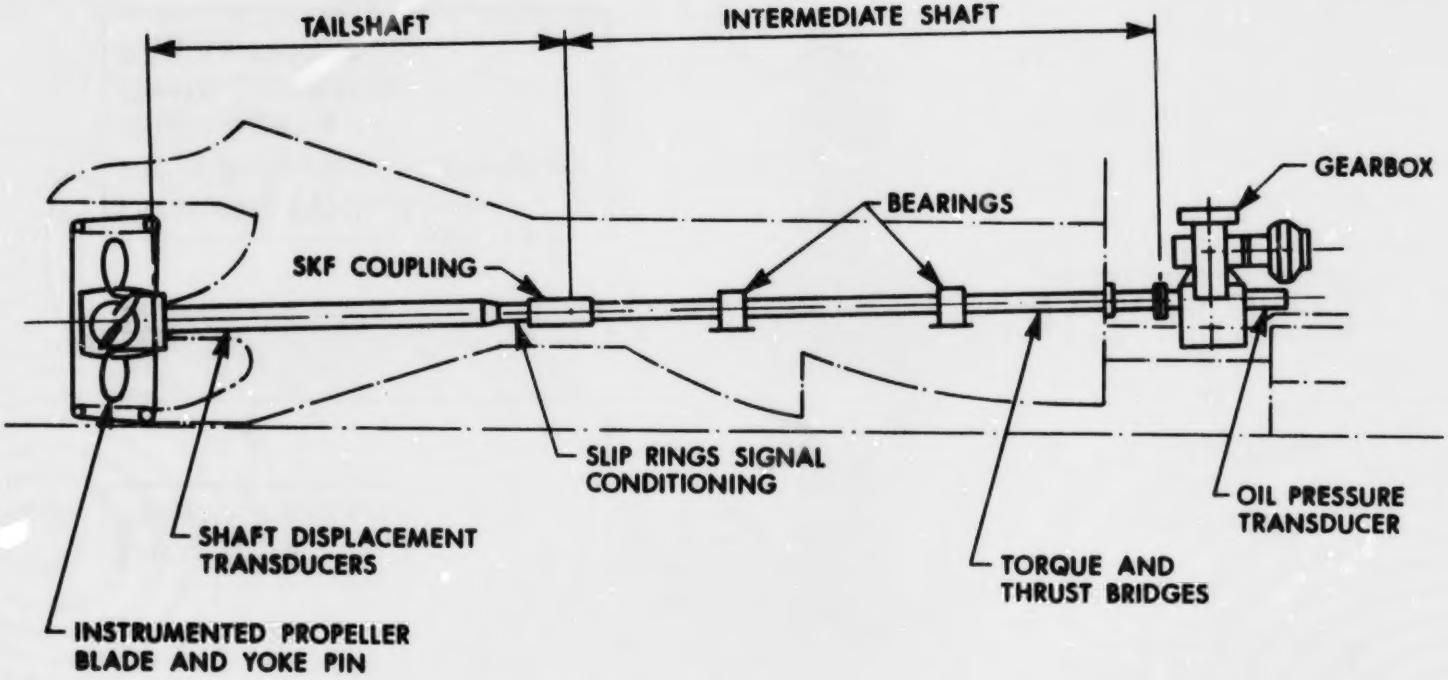
The quantities to be measured are shown in Figure 1.4.1 and the locations of the major transducers are shown in Figure 1.4.2. Loads on the propeller blade were determined from six strain gauge bridges mounted within one propeller blade. The sliding block of the yoke pin turning mechanism was instrumented and the signal wire routed through the propeller tail shaft to a point forward of the stern tube seal. There, signal conditioning equipment was situated and data was removed from the starboard shaft via slip rings. Shaft torque and thrust bridges were mounted on the starboard intermediate shaft and the data telemetered off the shaft. The torque and thrust data was used for both the detailed measurement and the collection of the interaction statistics over one operating season. Not shown in Figure 1.4.1 are four magnetic proximity probes used to measure the position of the tail shaft relative to the bearing surface.

Research activities that had to be performed, included: Re-instrumentation of the propeller blade; Complete disassembly of the starboard CPP hub; Replacement

# PROPULSION LOADS MEASUREMENT SCHEME


TRANSFER FUNCTION
Shaft Torque and Thrust
Location and Magnitude of Ice Loads
ICE LOAD
Long Term Shaft Statistics
DYNAMIC LOAD TRANSFER
Yoke Pin Stress
Propeller Pitch Angle
Pitch Actuator Oil Pressure
Shaft Speed
Shaft Orientation
Engine Fuel Rack

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER<br>INTERACTION PARAMETERS | TITLE: PROPULSION LOADS<br>MEASUREMENT SCHEME<br>FIGURE No. 1·4·1 |


TAILSHAFT
INTERMEDIATE SHAFT
GEARBOX
BEARINGS
SKF COUPLING
SLIP RINGS SIGNAL CONDITIONING
OIL PRESSURE TRANSDUCER
SHAFT DISPLACEMENT TRANSDUCERS
TORQUE AND THRUST BRIDGES
INSTRUMENTED PROPELLER BLADE AND YOKE PIN

CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE PROPELLER
INTERACTION PARAMETERS

TITLE: LOCATION OF TRANSDUCERS
STARBOARD SHAFT

FIGURE No. 1·4·2

of the signal cable within the tail shaft; Machining modifications to one propeller blade carrier; Installation of the instrumented sliding block; Re-assembly of the hub; Physical calibration of the propeller blade and yoke pin; Extensive modifications for the installation of the shaft movement transducers and associated wiring; Installations of pressure transducers, and; Replacement of the starboard shaft in the vessel.

Recording and analysis instruments were installed on the ship for a five day intensive field test program occurring in June/July, 1984. A total of 18 engine performance, ship performance, and stress signals were recorded during the intensive field program. Ice data was also collected during the test program.

## 1.5 Scope of Report

This report covers all of the engineering and development activities which occurred prior to and during the field test program. It also describes the field test program and the results of the physical modelling of the ice interaction phenomena. In some cases, collected data is presented, but this is only for the purpose of illustrating the capabilities and properties of the measurement system. Thus, the values given on the graphs, should be used with caution as they have not been subjected to the required intensive review and verification process. The results and conclusions of the data analysis and interpretation will be presented in the forthcoming reports of this project.

The design and installation of the transducers into the vessel is described in Chapter 2 along with details of the signal conditioning and data acquisition hardware and software. The extensive work associated with the calibration of the transducers is discussed in Chapters 3 and 4. Chapter 3 is devoted to the propeller blade including the use of 1983 calibration data to investigate the accuracy of using the propeller blade system as a "load-cell". Chapter 4 is concerned with the calibration of the yoke pin sliding block.

Chapter 5 describes the onboard data analysis capability and is illustrated with data collected during the intensive field test program.

The execution of the field test program is covered in Chapter 6. It includes data on the environmental ice conditions and observations of the behaviour of the wake and entrapped ice blocks made from the stern of the MV Robert LeMeur. A report on the performance of the instrumentation is also found in Chapter 6.

The analytical modelling work is described in Chapters 7 through 10. Chapter 10 contains examples of collected data to verify and illustrate the performance of the shaft dynamics model.

The Appendices contain extensive support material including listings of the software developed for the engineering and test phase components of the project and machine drawings of pertinent parts of the engineering development.

# 2. INSTRUMENTATION DESIGN AND INSTALLATION

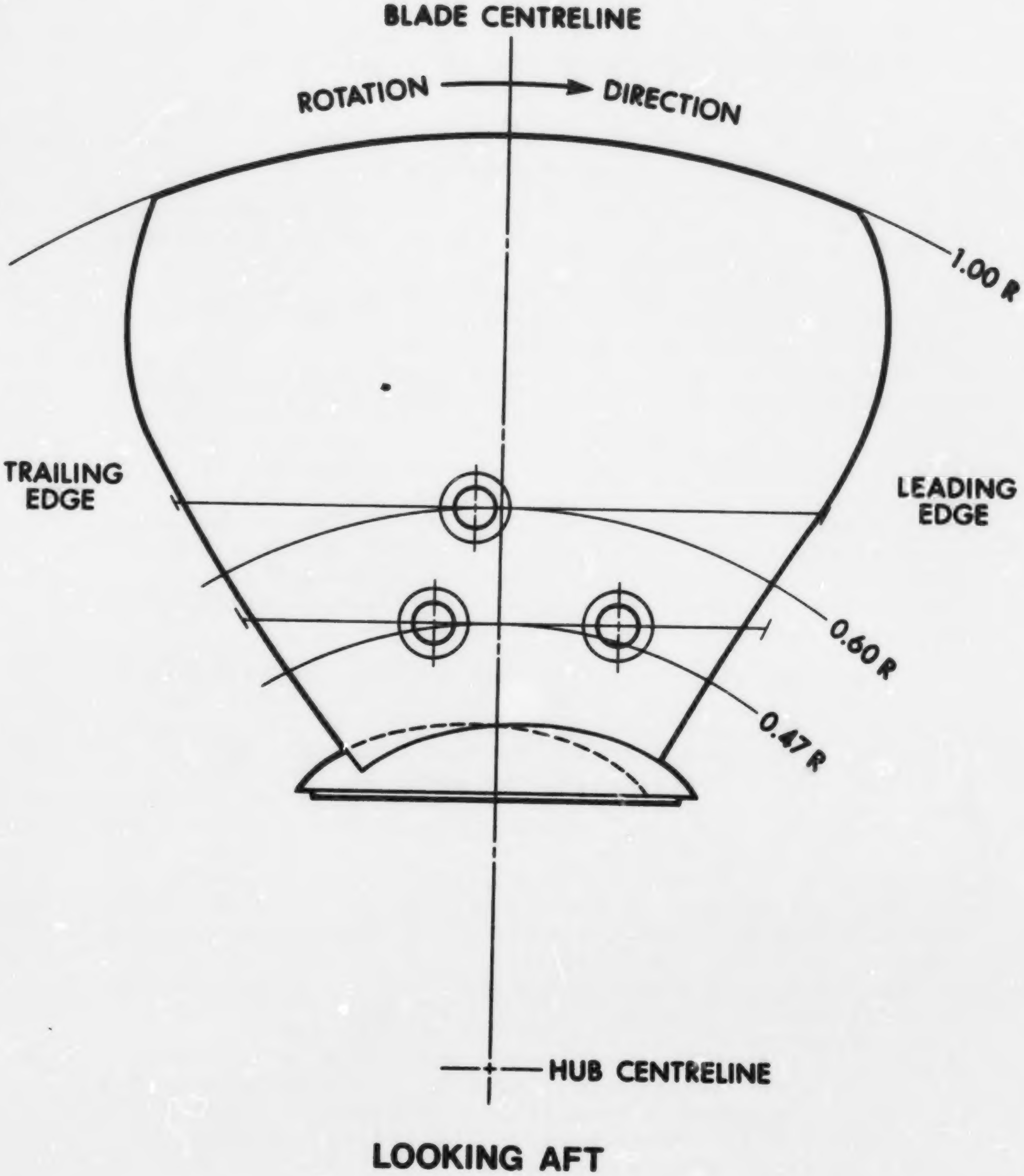
## 2.1 Propeller Blade Strain Gauging

Within the scope of the 1983 project, extensive work had been done to develop a methodology for the measurement of the ice induced loads on a blade of a CPP system including the development of a blade strain gauging arrangement, machining and preparation of the blade to receive the gauges, and preparation of a calibration and analysis methodology. The original design work for the gauge arrangement was performed by the Technical Research Centre of Finland Ship Laboratories under contract to Canmar and is described in detail in Reference 1.5. Because the physical calibration results and the limited full scale test data obtained in 1983, had provided encouragement that the methodology was feasible, though needing refinement, it was decided early in the definition phase of the 1984 project to use the same basic measurement approach, while addressing the deficiencies of implementation that had been encountered.

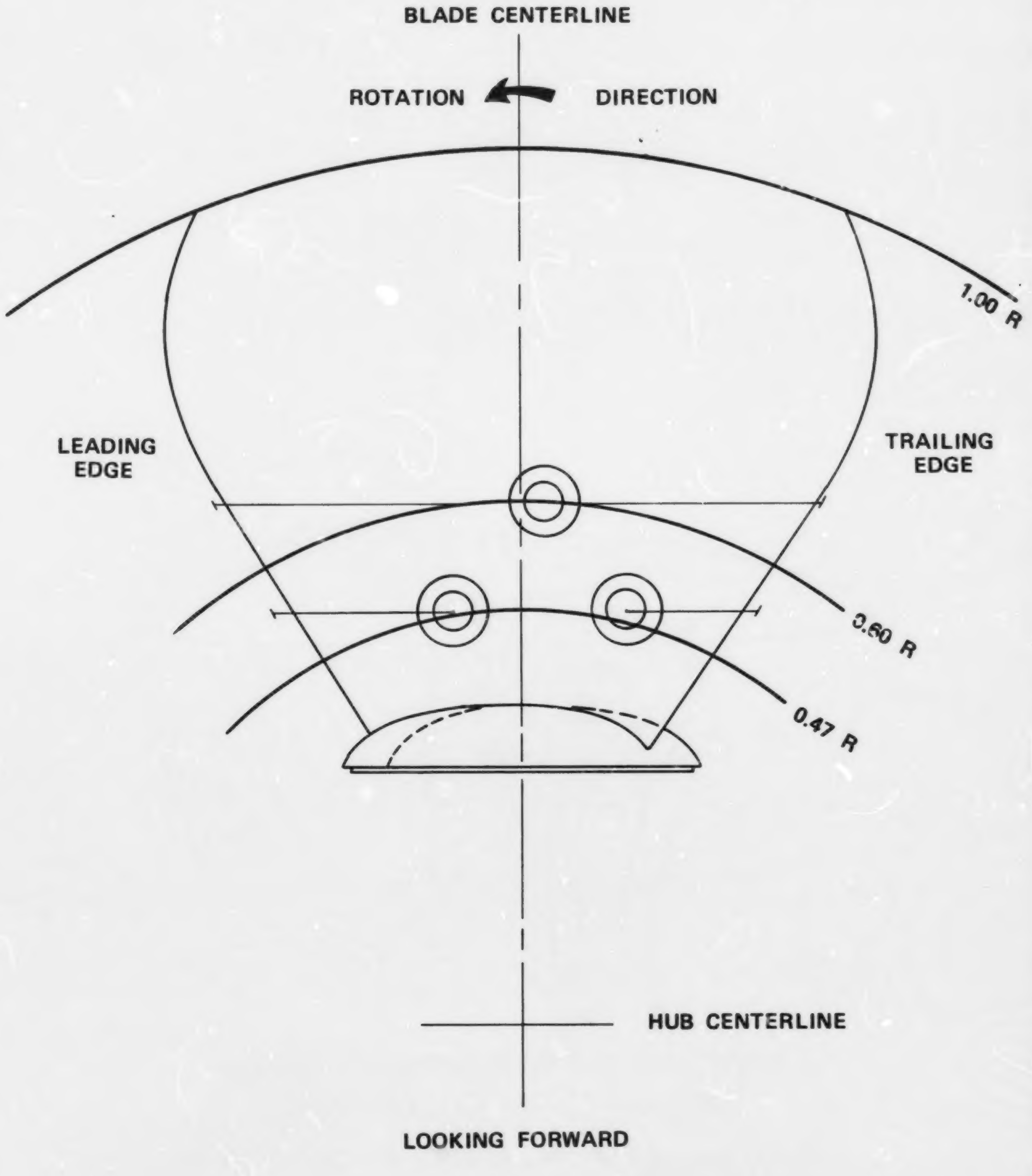
The 1983 methodology called for the use of three strain gauge full bridges (four active arms each) to measure shear associated with blade spindle torque, and three full bridges (four active arms each) to measure blade bending. These six strain gauge bridges were installed in six machined recesses, three on the suction side and three recesses on the pressure side of the blade as shown in Figures 2.1.1 and 2.1.2. Each bridge consisted of four strain gauge elements, two elements of which were mounted in a recess on the suction side, with the remaining two elements mounted in the recess directly opposite on the pressure side. Thus, a signal strongly correlated with spindle torque and another signal strongly correlated with blade bending was obtained at each of three locations distributed both radially and circumferentially on the blade. The installation and interconnection arrangements used in the 1984 program for the shear and bending bridges are indicated in Figures 2.1.3 and 2.1.4. respectively. The indicated state of strain in the blade in each case, is the one for which the bridges were designed to give positive outputs.

### 2.1.1 Inspection of the 1983 Installation

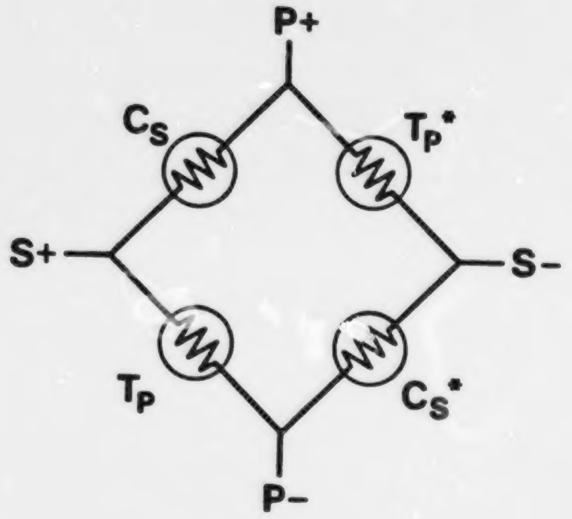
In the 1984 blade instrumentation task, emphasis was focused on identifying the causes of problems experienced

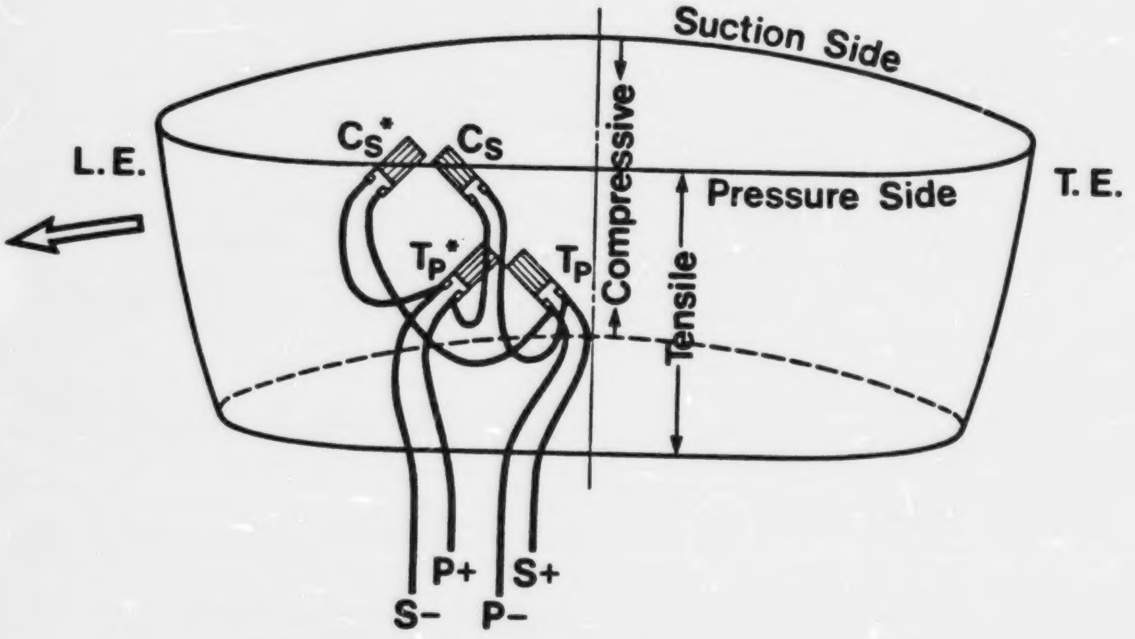

BLADE CENTRELINE
ROTATION
DIRECTION
1.00 R
TRAILING EDGE
LEADING EDGE
0.60 R
0.47 R
HUB CENTRELINE
LOOKING AFT

| | | |
|---|---|---|
| CANMAR<br>CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE:<br>INSTRUMENTED LOCATIONS ON BLADE SUCTION SIDE<br>FIGURE No. 2·1·1 |


BLADE CENTERLINE
ROTATION
DIRECTION
1.00 R
LEADING EDGE
TRAILING EDGE
0.60 R
0.47 R
HUB CENTERLINE
LOOKING FORWARD

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: INSTRUMENTED LOCATIONS ON BLADE PRESSURE SIDE |
| | | FIGURE No. 2.1.2 |


P+
$C_S$
$T_P^*$
S+
S−
$T_P$
$C_S^*$
P−


Suction Side
Compressive
L.E.
$C_S^*$
$C_S$
Pressure Side
T. E.
$T_P^*$
$T_P$
Tensile
P+
S+
S−
P−

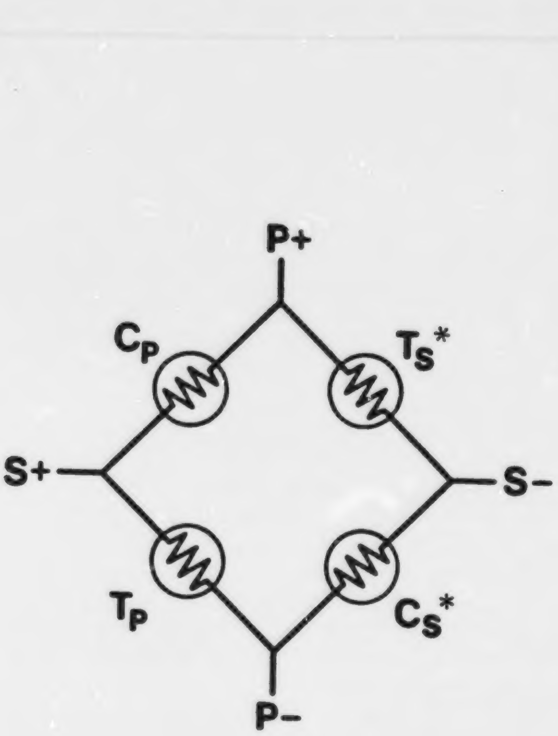
SECTION OF INSTRUMENTED BLADE
SHOWN LOOKING FORWARD

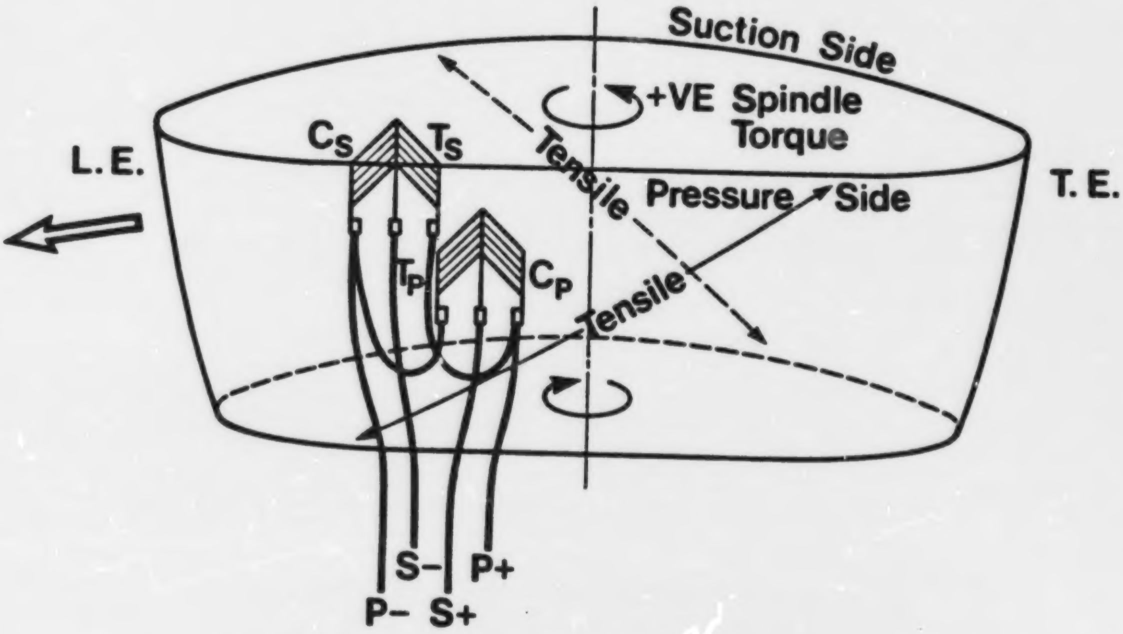
Strain gauges shown greatly exaggerated in size for clarity.

*Tp - Stands For: Tension, Pressure Side

Cs - Stands For: Compression, Suction Side

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE: BLADE BENDING<br>STRAIN GAUGE BRIDGE |
| | | FIGURE No. 2·1·3 |


P+
$C_P$
$T_S$*
S+
S−
$T_P$
$C_S$*
P−


Suction Side
+VE Spindle Torque
$C_S$
$T_S$
L. E.
T. E.
Tensile
Pressure
Side
$T_P$
$C_P$
Tensile
S−
P+
P−
S+

SECTION OF INSTRUMENTED BLADE
SHOWN LOOKING FORWARD

Strain gauges shown greatly exaggerated in size for clarity.
*Tp - Stands For: Tension, Pressure Side
Cs - Stands For: Compression, Suction Side

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE: BLADE TORSION STRAIN GAUGE BRIDGE<br>FIGURE No. 2·1·4 |

in the 1983 project and finding ways to reduce the likelihood of such problems occurring. In early November 1983 the MV Robert LeMeur was drydocked at McKinley Bay for the winter. At this time the instrumented blade was removed from the starboard CPP system and the strain gauge and cabling system was inspected. Data was obtained to examine the causes of failure of the strain gauge bridges experienced prior to the June 1983 test period.

The major finding was that the epoxy sealing of the cover plates that closed the machined strain gauge recesses in the blade surface, was largely missing and the screw fasteners that retained those plates were substantially loosened, two of them missing altogether. Within each of the recesses inspected, seawater had penetrated beneath the RPV sealant which covered the gauges and had corrosively attacked the gauges themselves. Indeed most of the gauges were completely corroded away, with only small portions of the gauge substrate material remaining in a few of the areas. Evidently the extremely high vibrational accelerations to which the blade was exposed in ice operations had destroyed the mechanical sealing against sea water and the chemical sealing properties of the RPV had been insufficient to isolate the gauges from the effects of the seawater.

The addition, there was some evidence of seawater incursion into the space between the blade foot and the blade carrier, though this was not extensive. The outer jacket of the 19 signal conductor cable within the shaft had evidently broken and was admitting hydraulic oil to the interior of the cable. The PVC jacket, though chosen for its oil resistance, was in fact brittle and in a state of significant deterioration, presumably as a result of its exposure to the CPP system hydraulic oil. Its outer shield was found to be in close electrical contact with the shaft itself, but all of the individual signal conductors within it continued to show high isolation from one another and from the shaft material.

### 2.1.2 Specifications for the 1984 Installation

In order to address the problems found with the 1983 blade strain gauge installation four principal steps were taken in specifying the 1984 installation:

- It was recommended that the Micro Measurements EA series open faced gauges used in 1983 be replaced with a more rugged gauge series. Ideally this would have been the WA series gauge which features total encapsulation of the foil resistive element, integral attached lead wires and high tolerance to vibration. Unfortunately these gauges were found to be available only at 8 to 14 week deliveries from receipt of order. As negotiations and approvals to proceed with the 1984 project were sufficiently late as to preclude this lead time, a more common gauge variety was substituted. CEA series encapsulated gauges were selected as the best alternative available from stock. These gauges also featured encapsulated grids but lacked integral lead wires and did not have the superior vibration tolerance of the WA series. Breaking of the connection between the grid foil and the copper solder tabs was acknowledged by the manufacturers to be a problem after greater than one hundred million cycles of strain at +/-1800 microstrain. Though the strain levels experienced by the blade were typically less than half of this, in most ice operations, the extreme vibrational shock to which it was to be exposed might have also tended to crack the connection between the foil grid and the solder tabs. This was mitigated to some extent by the use of low modulus solder but it was clear that this was a less than optimum solution. Only the fact that the project was committed to gathering data with the system immediately upon the undocking of the vessel permitted the specification of the CEA series with low modulus solder as there was clearly a risk of fatigue limited gauge life with this type.

- Improved chemical sealing of the gauges and lead wires against moisture incursion was recommended. Investigation of the curing properties of RPV rubber upon metal surfaces revealed that this widely used waterproofing agent was completely unsuited to strain gauge moisture protection. After discussion with the strain gauge manufacturer's applications staff, a liquid epoxy sealant that could be flowed into the strain gauge recesses and lead wire holes was selected. In addition, application procedures including the prior coating of the leadwire connections with nitrile rubber and the surface preparation of the bronze interior surfaces of the gauge recesses to bond to the liquid epoxy sealant were specified. At the same time, a fully sealed junction box, blocked with liquid epoxy, was designed for the base of the instrumented blade where the blade gauge lead wires were made into the shaft cable. Unlike the previous installation, where the cable's outer jacket was stripped off in the cavity beneath the blade foot, in the current installation case a packed, pressure tight gland was used to seal the fully jacketed shaft cable. It went into the blade foot junction box to further inhibit the incursion of seawater that could enter the blade foot cavity around the blade retaining bolts. Water could otherwise be drawn, under centrifugal force, into the wire passages in the blade and hence ultimately along the lead wires to the gauges.

- Improving retention of the blade recess cover plates was a third step taken in reducing past problems. As before, the blade cover plates were sealed with an "o" ring inside the radius of the ring of screws that secured it to the blade. It was decided, however, that it would be necessary to take some additional measures to prevent the loosening of the screws under the extreme shock and vibration experienced by the blade in ice operations. The preferred approach was to braze or weld the screws or the complete cover in place after the gauges had been mounted. This was rejected because, in view of the geometry of the recesses and the required temperatures for brazing, it was considered unlikely that this could be done without substantial risk of damaging the gauges or the insulation of the leadwires. Instead, it was decided to, once again, fill the cavities around the screw heads with metal epoxy. This time however, the heads of the screws were machined in such a way as to form a convex lip to keep the epoxy body from dropping out of the space. The epoxy body in turn would key the screw head against rotation.

- The final step was to improve oil resistance for the jacket and insulation of the multi-conductor cable to be installed through the CPP system hub and propeller shaft. It was determined that the only readily available insulating material that could offer the necessary degree of oil resistance was Teflon. No North American, Japanese or European supplier contacted was able to provide from their normal product lines, a Teflon cable with the required number of conductors, small overall diameter and internal construction that was required. Therefore, it was necessary to have one custom manufactured. Fortunately, a firm was identified that was willing to attempt the manufacture within the short available time of four weeks and this was duly supplied in full compliance with our specifications. Although the PVC cable appears to have had sufficient useful life to have permitted the collection of the propeller blade data, the cable was also an integral part of the oil sealing of several parts of the CPP system once it was installed, and in view of the deteriorated condition of the PVC cable it was judged to be too hazardous to the reliable long term operation of the CPP system to re-install such a cable.

### 2.1.3 Blade Strain Gauge Installation

In late April, S. Roger Saint of the Research Engineering staff arrived on-site and began the strain gauge installation. This involved the cleaning and preparation of the bronze surfaces within the recesses to receive the strain gauges, installation of new lead wires from the recesses through the drilled wire passages to the blade foot and bonding of the strain gauges. Following curing of the gauges (under clamping pressure over a 12 hour period), the lead wires were attached with low modulus solder and all electrical connections were coated with acrylic to provide electrical isolation and to seal the ends of the wire insulation and the gauge solder tabs.

Next, the recesses were poured full of a liquid epoxy sealant formulated by the strain gauge manufacturer to provide a durable moisture seal. This compound was used to fill the recesses flush to the level of the stepped rim of the recess against which the bronze cover plate fits. Care was taken to keep this rim clean as it was the mating surface for the "o" ring seal as indicated in Appendix J, Drawing A2 11020.

The "o" rings were then placed in the cover plates, additional epoxy was applied to the central portions of the underside of the covers, taking care to keep the quantities small enough to ensure a good filling of the cavity without extruding the material as far as the "o" rings. The covers were then set in place and secured with the retaining screws. Lastly, metal epoxy was forced into the gaps surrounding the screw heads and into the gaps at the periphery of the covers and when this had set, it was ground flush with the blade surface.

During late April and early May 1984, the starboard rudder of the MV Robert LeMeur was removed, the starboard propeller shaft was removed from the ship, the remaining three blades were removed and the hub disassembled. In the third week of May, additional staff from the Research

Engineering group arrived, together with two Lips Field Engineers. The old PVC cable was removed from the tail shaft and the new Teflon clad cable was installed in its place. The hub internals were then reassembled, routing the cable through the specially modified blade carrier. The instrumented sliding block was installed at this time and its lead wires routed through newly drilled and glanded holes in the blade carrier. The yoke was then replaced, the hub closed and the two uninstrumented blades were mated to the hub. The instrumented blade was positioned beneath the hub with its base facing the blade carrier and about 15 inches clearance between the two. A prepared brass junction box was secured to the base of the blade over the lead wire opening. The main Teflon clad signal cable from the blade carrier was glanded into this box, as was the smaller lead from the sliding block bushing. With the junction box cover plate removed, all of the electrical connections were made with soldered splices protected by melt sealing heat shrink. The wires were arranged within the junction box and the box was poured full of the same liquid epoxy used to seal the gauge recesses. The cover was then secured in place.

The cavity within the blade carrier, in which the loops of the main signal cable and the sliding block lead were free to flex, was packed with a light silicon grease, tested for low viscosity at freezing temperatures. Finally, the instrumented blade was raised near enough to its blade carrier to permit the blade retaining bolts to be inserted through the blade and started in the blade carrier. Taking care to keep the cable and sliding block leads within the cavity, the blade was slowly raised and secured in place by tightening these bolts. At each stage in the assembly, the integrity of the strain gauges and cabling was verified by electrical continuity and isolation checks as well as by strain bridge balance checks from the free end of the main signal cable.

Personnel involved in this stage of the instrumentation on-site were:

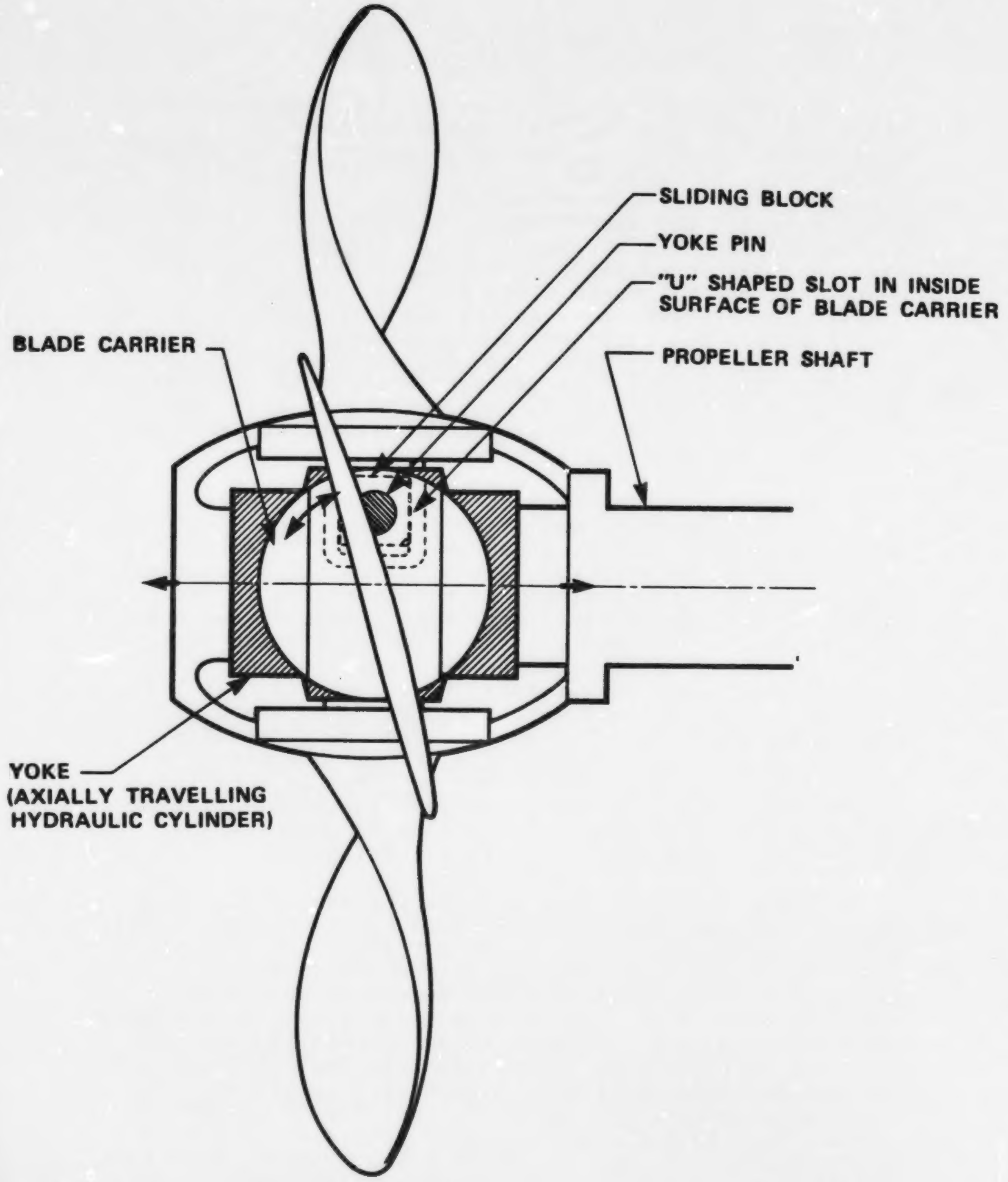
| | |
|---|---|
| Merv Edgecombe | Supervisor, Research Engineering |
| Howard Bergen | Electrical Engineer, Research Engineering |
| Ken Kirby | Mechanical Engineer, Research Engineering |
| Adrian Notenboom | Site Manager, Construction |
| Rob Dinkelaar | CPP Field Engineer, Lips BV |
| Tom Hofmann CPP | Field Engineer, Lips BV |
| Nigel Hastings | Acting Chief Engineer, CANMAR Marine Operations |

## 2.2 Sliding Block Strain Gauging

In developing the proposal for the 1984 propeller blade load test program, the CANMAR Engineering Development group urged that measurements of the spindle torque actually resisted by the pitch setting mechanism within the hub be made, in addition to the measurements of spindle torque obtained from the blade strain gauges. The motivation for this was to check the design assumptions that are made concerning the degree to which ice and hydrodynamically induced blade spindle torques are resisted by friction between the blade carrier and the hub body, thereby reducing the forces that must be resisted by the yoke pin sliding block assembly and the hydraulic system. (The pitch setting mechanism for this propeller is diagrammed schematically in Figure 2.2.1 to help the reader understand how these components work together to set and hold the propeller pitch).

Accordingly, the project team evaluated several alternative methods by which the spindle torque resisted by the yoke pin could be measured. Initially, strain gauging of the base of the yoke pin itself was considered, the object being to measure the root stresses in the fillet at the base of this structure. This approach was finally rejected on two counts: firstly, that the stress field at such a point would be very complex, making stresses difficult to interpret in terms of actual load carried by the pin; and secondly, that the minute size of the gauges that would be required and the difficulty of routing lead wires from the base of the yoke pin to a point where they could be joined into the main tailshaft signal cable made the design of such an installation a major problem that could easily come to dominate the project both financially and in scheduling.

The alternative that was elected involved strain gauging the two load carrying faces of the sliding block bushing that transmit the pitch setting force from the yoke pin to the blade carrier. As shown in Figure 2.2.2, recesses were machined into the centre of each load carrying face of the sliding block and strain gauges were mounted on the walls of each recess normal to the load carrying surface. The expectation was that the gauges in one recess would experience compressive strain when the block was loaded on the adjacent face and the gauges in the opposite face would experience little or no strain. By connecting the four gauges in a full bridge, with the two gauges in a given recess in diagonally opposite legs of the bridge, a positive bridge output would be obtained for load on one face of the sliding block and negative


SLIDING BLOCK
YOKE PIN
"U" SHAPED SLOT IN INSIDE SURFACE OF BLADE CARRIER
BLADE CARRIER
PROPELLER SHAFT
YOKE
(AXIALLY TRAVELLING HYDRAULIC CYLINDER)

CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE
PROPELLER INTERACTION
PARAMETERS

TITLE:
PITCH SETTING MECHANISM

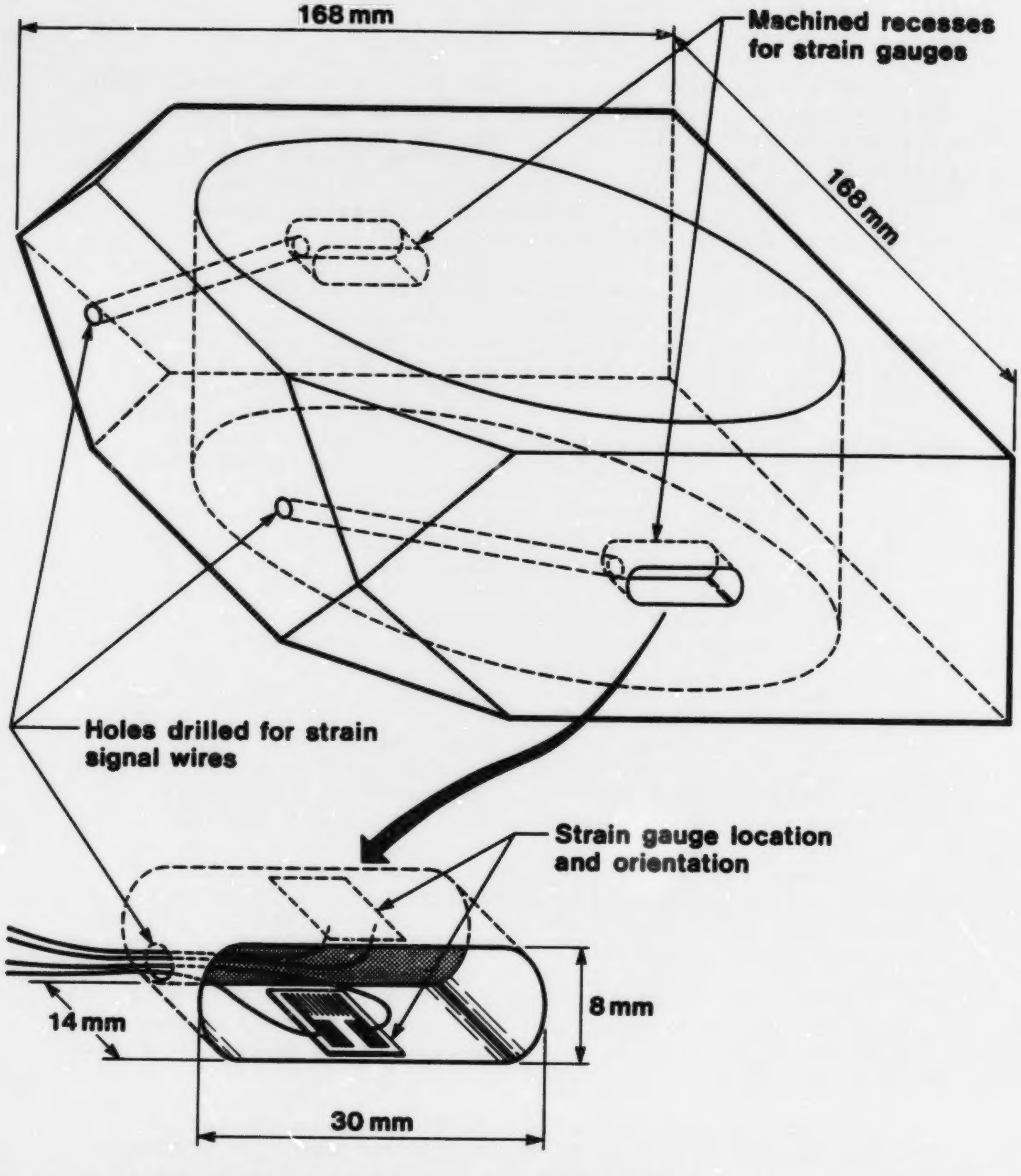
FIGURE No. 2.2.1

output would be obtained for load on the other face. Thus spindle torque in either sense could be estimated by determining the load from the bridge output and multiplying this load by the effective moment arm from the centre of the yoke pin to the centre of the blade carrier. The length of the moment arm is a simple geometrical function of the pitch setting.

This approach had the advantage that the actual sliding block was a relatively small piece to work with, compared to the yoke casting (kilograms vs hundreds of kilograms). It could, therefore, be loaded in a laboratory machine in much the same way as it would be loaded by pitch setting forces in the hub. This permitted a physical calibration of the strain gauge output vs applied load to be obtained. Like the instrumentation of the yoke pin, however, the routing of the lead wires from the sliding block to the main signal cable presented a major difficulty. Originally it was planned to bring the lead wires out through the unloaded face of the sliding block that was nearest the centre of the blade carrier. From that point they would be glanded through the blade carrier and would be spliced into the main signal cable in the blade foot junction box that was within the blade carrier cavity. Sufficient slack would be left between the sliding block and the blade carrier glands to permit the lead wires to flex. This would accommodate the relative motion of the sliding block and the blade carrier as the sliding block advanced and retreated radially, relative to the blade carrier slot, as pitch was changed.

It was recognized that the arrangement would have limited useful life as the lead wires would be expected to fatigue and eventually fail under the constant rotational and pitch setting motions. However, the design of sliding contacts and brushes, or short range telemetry to transmit the signal between the moving parts was clearly beyond the financial and time constraints of the project and was not judged to offer significantly better prospect of long term reliability.

In the actual installation the strain gauges were applied to the sliding block, which was made of Lidrunal bronze, using the following procedures. A small cavity was machined in both interaction faces of the sliding block. Each was made 14 mm deep to accommodate the length of the selected gauges. To allow access for surface preparation, gauge mounting and wiring, the cavity cross section was made rectangular with 30 mm and 8 mm sides. Holes of 3 mm diameter were drilled from the cavities to a non-contacting face so the signal wiring could be brought out. Figure 2.2.2 shows a sketch of the sliding block modifications and strain gauge locations.


168 mm
Machined recesses for strain gauges
168 mm
Holes drilled for strain signal wires
Strain gauge location and orientation
8 mm
14 mm
30 mm

HOLES AND RECESSES FILLED WITH M-COAT GL POLYSULFIDE MODIFIED-EPOXY, AFTER GAUGE INSTALLATION

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE: SLIDING BLOCK MODIFICATION<br>FIGURE No. 2·2·2 |

Four Micro-measurement, CEA-06-125 UV-350, Constantan grid, polymide encapsulated strain gauges were fitted into the block cavities using the following procedures:

a - degrease cavities and wiring holes with chloroethene NU.
b - abrade gauge location area with 320 grit paper.
c - abrade gauge location area with 400 grit paper.
d - wet abrade area with 400 grit paper and a weak acid conditioner (Conditioner 'A').
e - scrub area with Isopropyl alcohol and cotton swab.
f - wipe area clean.
g - neutralize area with distilled water and cotton swab.
h - wipe area clean.
i - open gauge envelope and place gauge down on clean surface.
j - with 7 cm of cellophane tape stick down and pick up gauge leaving 4 mm of tape beyond the top of the gauge.
k - position gauge in the center of the prepared area in cavity with the gauge solder terminals facing out of the cavity.
l - stick 4 mm section of tape to back of cavity.
m - prepare a mixture of M-bond ME-10 epoxy.
n - carefully apply a thin film of epoxy to the underside of the gauge and to the mating gauge area.
o - holding the 4 mm section of tape with a probe, lower the gauge into location and press out excess epoxy from the inside to the outside of the cavity.
p - remove any excess epoxy from cavity and place a second piece of cellophane tape over the gauge and 30 mm surface length.
q - put a silicon gum pad over gauge.
r - tape pad into place.
s - wedge an aluminum cover plate into the cavity to provide compression of the silicon pad over the gauge.
t - let epoxy cure for 12 hours.

After all four gauges were bonded into location, the cellophane tape was removed. Wiring and protection were applied using the following :

-Wire: 36 AWG stranded, silver plated copper wire with colour coded, pre-etched, Teflon insulated wire.

-Solder: $242^{\circ}$F melt temperature, TIN/INDIUM 0.5 mm diameter, solid low modulus solder.

-Flux: Non-corrosive resin flux.

The procedures were as follows:

a - cut wire to provide four twisted pairs one metre in length each.
b - strip off 2 mm of Teflon insulation from the ends of the wires.
c - thread two twisted pairs of wire into each gauge cavity through the 3 mm access holes.
d - flux and tin solder tabs and wires.
e - loop wires to provide strain relief in cavity.
f - solder wires to tabs.
g - remove excess flux with resin flux solvent.
h - apply a coat of M-coat D acrylic protection to gauge, solder tabs and any bare lead wire.
i - allow 30 minutes for coating to dry.
j - prepare a mixture of M-coat GL two part 100% solids polysulfide modified-epoxy compound.
k - paint M-coat GL onto all gauge and wire surfaces.
l - fill wire access holes with M-coat GL liquid.
m - fill cavity with M-coat GL liquid.
n - put cellophane tape over cavity opening and let epoxy cure for 24 hours.

The cured epoxy produced a tough, rubbery potting in the strain cavities, giving a flat exterior surface, flush with the sliding block contact faces.

Because the lead wire holes in the sliding block were drilled to the wrong face during manufacture, (contrary to specifications), it was necessary to change the lead wire routing scheme on-site as there was insufficient time to modify the sliding block or reinstrument and recalibrate it. This involved drilling a 5 mm diameter hole radially inward from the edge of the blade carrier at the high radius end of the sliding block channel to meet the original drilling from the blade foot cavity to the low radius end of the channel. The lead wires were brought out from the face of the sliding block and looped over the edge of the blade carrier and fed into the 5 mm drilling, leaving enough slack to accommodate the differential motion of the sliding block and blade carrier. The lead wires were passed through a brass stuffing gland into the blade foot cavity and were then glanded into the blade foot junction box where they were spliced to the main signal cable. The exposed lead wires at the surface of the sliding block were coated extensively with nitrile rubber to distribute bending away from the surface of the block and to protect them against abrading on adjacent metal surfaces.

In retrospect this arrangement was probably just as satisfactory as the planned routing scheme and proved to be a much simpler assembly procedure than the original system would have been, given the inaccessibility of the low radius end of the sliding block channel in the blade carrier during final installation of the yoke assembly.

### 2.3 Shaft Movement Instrumentation

In addition to the instrumentation of the sliding block, the CANMAR Engineering development group proposed an addition to the 1984 Propeller Blade Load Measurement Program to measure the transverse movements of the propeller shaft within the aft stern tube bearing. In normal ice-free operation the shaft should roll on a thin film of lubricating oil without actual mechanical contact between the shaft surface and the bearing. It was suggested that when ice passed through the propeller, transverse forces on the propeller disturbed the equilibrium lubricating process and the shaft could "bottom" against the bearing. Over time, this hard contacting of the two surfaces could be responsible for the deterioration of the bearing surface.

By measuring the relative motion of the shaft and bearing along two different radii and processing the data appropriately, it was possible to plot the "orbit" of the shafting within the bearing. Such techniques were commonly used in the diagnostic investigation of vibration problems in heavy rotating machinery such as compressors as turbines. For the purposes of this test programs it was proposed that such measurements be made both fore and aft of the aft stern tube bearing. By recording all of the outputs on a common time base, it was hoped that information on the bending behaviour of the tail shaft and the longitudinal distribution of contact within the bearing could be obtained, as well as information on the rotational trajectory of the shaft in the bearing.

The method commonly used to measure transverse shafting movements in rotating machinery involves the use of electro-magnetic proximity probes. These consist of a small coil excited with a radio-frequency (R.F.) signal and are supported near the surface of the shaft, commonly from a bearing face. As the distance from the ferro-magnetic surface of the shaft to the coil changes, the reluctance of the magnetic circuit linking the turns of the coil, and hence the coil impedance, varies. If the coil is configured as part of a tuned R.F. circuit the frequency of the R.F. signal changes in response to changes in the gap length and this frequency change is detected and converted to a DC voltage output. A wide variety of such transducer systems are available from a number of manufacturers' of industrial control and measurement equipment. Such measurements are a standard and routinely used tool for the analysis of many types of machinery problems, however, such measurements are most often made in relatively benign environments where there is easy access to the transducer location.

In these tests, the transducers had to be located in completely inaccessible areas, exposed to very high levels of vibration over long periods of time. The associated electronics, which had to be located within a strictly limited cable run length of the transducer, would have to be installed in a seawater ballast space. Moreover, it was determined that it was not feasible to operate the MV Robert LeMeur in ice without flooding this space as this was essential to trimming the vessel properly.

Although custom made probes, cables and electronics packages were available from many manufacturers for installation in severe environments, demand for such systems was low and they were never stocked. Manufacturing lead times were typically three months for such specialized equipment. Unfortunately, this addition to the program was proposed very late in the mobilization phase leaving only about four weeks to procure the necessary components. As a result, the only option available was to use conventional components and to attempt to work out a suitable installation and protection scheme that could be implemented with materials available on-site at McKinley Bay.

Bentley-Nevada type 7200 proximity probe systems were specified for this application. They consisted of a 5 mm diameter probe, a tuned 9 mm length of Teflon clad coaxial signal cable, and the signal conditioning electronics unit. In addition, a large quantity of water-tight cable glands and two water tight enclosures for the electronics units were procured from Bentley-Nevada. The installation plan, developed jointly between the Research Engineering staff and the Engineering Development group called for the installation of two probes, approximately 90 degrees apart, in the shaft seal housing aft of the aft starboard stern tube bearing. Two more probes, also 90 degrees apart, installed through the stern tube casting forward of this bearing were required. The aft pair of probes were installed at approximately the 8:30 and 11:30 o'clock position on the seal housing as seen looking forward and the forward pair at the 10:30 and 1:30 positions in the stern tube. They were labelled the Aft Port, Aft Top, Forward Port and Forward Starboard probes, respectively.

The stated clearance in diameter between the new metal aft stern tube bearing and the tailshaft was given as 0.6 to 0.7 mm. The type 7200 proximeters were selected for their linear measurement range which extends from 0.05 mm to 2.5 mm and their availability from stock.

Due to the variances from the as-built drawings discovered in the actual structure, it was necessary to substantially alter the installation procedures that had been developed beforehand. This involved situating the forward pair of probes further forward than had been originally planned and substantially altering the support and sealing arrangement for the probes.

After the starboard propeller was reinstalled in the stern tube, the four probes were fixed in place with the clearance between the probe tips and the shaft surface adjusted to lie in the range 1.0 to 1.25 mm with the shaft supported in air in its bearings alone. In order to install the forward probes, access holes had to be cut through the outer stern tube and the skeg side shell plates. Special probe holders were fabricated to permit the probes to be installed, adjusted for clearance, sealed against oil from the shaft side and sea water from the ballast space side, and locked in place. To ensure against unlocking of the probes under the extreme vibration in these areas, the probe holder locking nuts were also spot welded in place.

In order to route the two signal cables from the aft pair of probes installed in the shaft seal housing, a schedule 80, high tensile steel half pipe was welded to the outside of the stern tube shell. It extended from the rope guard, which covered the seal housing, forward to the side fairing plate that formed part of the shell of the number seven water ballast tank in which the proximeter electronics were to be located. The cables from the two aft probes were routed over the outside of the seal housing beneath the rope guard and into the end of the sealed half pipe through two brass and rubber cable glands. They were passed through this half pipe, through a second set of glands installed in the ballast tank shell and into the ballast tank where they were glanded into the water tight junction box that housed the two signal conditioning amplifiers. The cables from the forward two probes were run directly through glands in the outer stern tube and into the ballast tank where they were glanded into a second water tight junction box which contained an additional pair of the electronics units.

Finally, multi-conductor cables were installed from the water tight junction boxes, through glands in the ballast tank forward water-tight bulkhead, and spliced into one of the ship's permanent R&D signal cables installed between the starboard shaft tunnel and the ship's electronics room. Via this connection, DC power was supplied to the proximeter electronics in the ballast tank and the signals were brought out to the data acquisition system.

At each stage in the installation, electrical tests and checks were performed to ensure the integrity of the probes and cables. After all of the welding was completed, the propeller was rotated and the shafting shifted within the bearing clearance by hoisting on the propeller blades with chain blocks. The outputs of the four probes were observed to verify that all were operational. Additionally, with the propeller supported in the bearing alone, baseline probe outputs were recorded at various angular orientations of the shafting, spanning a full 360 degrees. Similar checks were made with the ship afloat immediately after undocking.

### 2.4 Additional Transducer Systems

In addition to the six propeller blade strain gauge bridge signals, the sliding block strain gauge bridge signal and the four shaft movement signals, eight other signals were available to be recorded on the same data acquisition time base. These were:

- Starboard Shaft Torque
- Starboard Shaft Thrust
- Starboard Shaft Speed & Orientation
- Starboard Propeller Pitch
- Starboard Rudder Angle
- Starboard Propeller Main Servo Differential Oil Pressure
- Ship Speed
- Starboard Engine Fuel Rack

#### 2.4.1 Shaft Torque and Thrust

The starboard propeller shaft torque and thrust were important quantities required in addition to the propeller blade signals to give a complete picture of the ice impact phenomenon. In the 1983 test program these two quantities were measured at two separate locations on the starboard shaft line.

The MV Robert LeMeur had a permanently fitted torque and thrust monitoring system installed on the starboard intermediate shaft just aft of the aft engine room bulkhead. This system used a conventional strain gauge torque bridge which was compensated for shaft bending, and an Hylarides type thrust bridge, compensated both for shaft bending and for cancellation of torque influence due to thrust gauge misalignment. The two signals were telemetered off the shaft as FM analog data by an inductively powered, shaft-mounted electronics package. The 3 db bandwidth of the signals were 0-500 Hz.

In addition to this system, the 1983 program made use of a similar pair of strain gauge bridges mounted just forward of the forward stern tube seal. These signals were conditioned in the same shaft-mounted strain gauge signal conditioning package supplied for the blade signals and, like the blade signals, were removed from the shaft through slip ring and brush assembles.

Because the outputs of all four bridges were recorded on a common time base in the 1983 program, it was possible to compare the signals at the two locations. It was found that phase and amplitude differences between the two locations due to dynamic effects were negligible on the time scale over which significant ice/propeller interactions occurred. As a result, it was decided that in the 1984 program only the permanently installed torque and thrust monitoring system would be used.

Because an observed, once-per-revolution variation in the thrust signal, available from this system was believed to be due to improper mounting of one of the non-active legs of the Hylarides bridge, a second such bridge was installed prior to the commencement of the 1984 tests and was connected to the shaft electronics in place of the original bridge.

### 2.4.2 Shaft Speed and Orientation

MV Robert LeMeur is provided with a permanently installed shaft speed and orientation monitoring system for the starboard propeller shaft. The system consists of two electromagnetic proximity switch pickups mounted adjacent to the intermediate shaft near the torque and thrust monitoring system. Opposite the two pickups, two bands are clamped to the shaft. One of these contains a single ferro-magnetic tab at known angular origination relative to the instrumented blade of the starboard propeller. A single pulse is transmitted by this pickup once-per-revolution as the tab passed beneath it, at which moment the angular orientation of the propeller is thus established. The second band contains 40 such tabs so that its pickup produces a train of 40 pulses per revolution from which a wider bandwidth estimate of shaft speed can be obtained than is possible from the once-per-revolution pulse.

Frequency-to-voltage circuitry was also provided to convert the pulse trains into analog voltage levels proportional to shaft speed. For the purposes of this program, however, this circuitry was bypassed and the two pulse trains were sent directly to the data acquisition system. There it was intended that they should be summed together with different gains such that a single pulse train consisting of 40 low amplitude pulses and one high amplitude pulse per revolution would be recorded on the same time base as the rest of the data. In practice, it was discovered that the 40 pulse per revolution system was not functional. Since the additional information provided by this part of the system was considered to be of marginal importance, only the once-per-revolution signal was used.

### 2.4.3 Starboard Propeller Pitch and Rudder Angle

For the purpose of control of the CPP system, the propeller manufacturer provided for the continuous measurement of the pitch setting of the propeller. A mechanical feedback linkage extended from the hydraulic servo in the propeller hub, through the innermost oil supply pipe in the shaft, to the oil distribution control box which was mounted just forward of the main reduction gear. A potentiometer in the oil distribution box was driven by this linkage in such a way as to produce an analog signal proportional to the angular pitch setting of the propeller blades. The signal was conditioned so that it was linear with pitch angle for both ahead and astern pitch, but with a different slope, expressed in volts per degree, for the two regimes. This peculiar arrangement was evidently used so that the same full scale voltage was obtained for "full" astern pitch as for "full" ahead pitch, despite the fact that the maximum angle to which the blades could be pitched astern was significantly less than that to which they could be pitched ahead.

Permanent provision was made onboard the MV Robert LeMeur to make this signal available for recording through a buffer that protected the ship's control electronics from any loading effects that might be introduced by the recording system.

An essentially similar arrangement was available to permit recording of the angular position of the rudders. A potentiometer connected to linkages in the steering control system was provided by the steering gear manufacturer to drive the bridge rudder angle position indicators. A buffered recording output was also a part of the ship's permanent instrumentation facilities.

### 2.4.4 Starboard Propeller Main Servo Differential Oil Pressure

Within the oil supply pipes in the propeller shaft, two annuli connected either side of the main hydraulic servo in the hub to the spool valve in the oil distribution control box. At the oil distribution control box two ports were provided through which the hydraulic oil pressure in the supply annuli was controlled by the spool valve. They also provided the actuating force at the main servo required to hold a given pitch setting against the hydrodynamic forces acting on the propeller blades, or to adjust their pitch.

It was anticipated that ice impact forces on the propeller blades that produce significant spindle torque transients would cause the hydraulic oil pressure across the main servo to fluctuate. By measuring the fluctuations it was believed that additional information concerning the loads experienced by the hub internals during ice/propeller interaction would be obtained. Such data could provide a useful check on the information obtained from the instrumented sliding block.

To measure the pressure across the main servo, a Schaevitz Differential pressure transducer was connected between the oil distribution control box ports. The maximum operating oil pressure of the hydraulic system in open water was normally about 50 bar which was the pressure required to hold full ahead pitch at maximum rated RPM. The pressure transducer was selected to have a measurement range of +/- 136 bar to allow headroom for higher transient pressures associated with pitch changing and ice impact loads. The pressure transducer selected was a strain gauge type with excitation provided from a DC supply located in the ship's electronics room.

### 2.4.5 Ship Speed Log

MV Robert LeMeur is fitted with an Ylinen NMD-3 dual antenna microwave speed log specifically designed to measure the speed of ice-going vessels relative to the surrounding ice cover. Past experience with this instrument has shown it to provide a reliable indication of ice transitting speed in continuous ice cover for speeds above about 1.15 knots when properly adjusted. However, transient speed information, such as in ramming operations, is lost due to the heavy filtering provided in this log's signal conditioning. In addition the signal contains information on the magnitude of the speed only. Astern speeds produce an output of the same sense as ahead speeds since the log is based upon measurement of the doppler beat frequency between a transmitted and a reflected signal. The output is available as both an analog voltage, linear with ship speed and as a pulse rate, suitable for input to certain types of marine satellite navigation equipment. In this application the analog output was fed to the data acquisition system for recording on a common time base with the other signals permitting the dependence of the ice/propeller interaction phenomena upon this basic quantity to be investigated.

### 2.4.6 Engine Fuel Rack

The amount of fuel metered into each cylinder per firing cycle is controlled by a mechanical linkage called the fuel rack. A potentiometer controlled by the position of the rack provides an electrical output used in the engine control system. Circuitry was installed which allowed access to the fuel rack electrical transducer output. The electrical output could be calibrated in mm (the unit used in specifying the engine curves by the manufacturer) by physically blocking the fuel rack, recording the electrical output and recording the reading on the graduated plunger attached to the fuel rack. In this system, 100% power corresponds to a rack of approximately 34 mm.

## 2.5 Signal Conditioning and Data Acquisition

### 2.5.1 Strain Gauge Signal Conditioning

In the 1983 test program, a shaft-mounted package of eight strain gauge signal conditioning amplifiers, based upon the Analog Devices 2B31J part, had been used to transform the millivolt outputs from the propeller blade strain gauge bridges and shaft torque and thrust bridges into high level signals having a full scale range of +/- 10 volts, suitable for transmission off the shaft through slip rings. Because this package had proven reliable and the components were readily available from the manufacturer, a second such package based on the same part was assembled for the 1984 program. It is listed in Appendix C.

Each signal conditioner consisted of a single printed circuit board containing the 2B31J amplifier module and potentiometers, to permit output, zero, and gain adjustment, as well as points for shunt calibration of the strain gauge circuit. Each card was provided with a two pole Butterworth low pass filter on its output, configured for a 3 db cutoff at 250 Hz. This frequency was chosen based on the observation from the previous year's data that the highest natural frequency contributing significantly to the total strain amplitude was due to a blade tension mode at approximately 90 Hz in water.

Eight of these cards were installed in a chassis strapped to the propeller shaft just aft of the coupling that joined the tailshaft to the intermediate shaft. All cards were powered from a common 24 volt DC supply through a dedicated set of slip rings. Each amplifier card contained its own regulated strain gauge bridge excitation supply, with the excitation level adjustable via a card edge potentiometer. Two slip rings were provided as parallel signal commons and one ring was dedicated to each high level strain gauge output. Eight signal conditioning amplifiers were provided in the chassis, including one installed spare. Additional spares of all components were carried onboard for both the signal conditioning and the slip ring assembles.

The 32 conductor tailshaft cable connecting the seven strain gauge bridges in the blade and the sliding block with the shaft-mounted signal conditioning was routed through the outermost oil annulus in the tailshaft. This was the "return" oil passage that permitted designed-in oil leakage, which lubricated the moving components in the hub, to return through the shaft to the CPP system oil reservoir. At the tapered section of the tailshaft, just forward of the forward stern tube seal, the cable was brought out of the annulus to the surface of the shaft through an oil-tight gland. The end of the cable was then strain relieved into the signal conditioning chassis and the individual conductors were soldered directly onto the cards to avoid any possibility of intermittent or variable electrical contact in the low level signal paths.

For five of the six blade strain gauge bridges, conventional four wire full bridge connections to the signal conditioning units were used. For the blade bending bridge in the centre recess, which was a particularly important signal, six conductors were used in two, three wire, half bridge connections which were then paralleled into a single full bridge at the signal conditioner. The same arrangement was used for the sliding block bridge. This permitted the maximum flexibility in reconfiguring the bridge connections at the signal conditioner if any element of the bridge were to fail, so that data could still be obtained from the remaining intact elements.

From the slip ring brushes the high level strain gauge signals were fed on 100% shielded, 22 AWG, multi-conductor signal cable to the ship's electronics room and the data acquisition master distribution panel.

### 2.5.2 Data Acquisition System

In the ship's electronics room, located just beneath the bridge, all of the signals were fed to a master distribution panel. The nineteen signals available were:

- Blade Centre Bending
- Blade Leading Edge Torque
- Blade Trailing Edge Bending
- Blade Centre Torque
- Blade Leading Edge Bending
- Blade Trailing Edge Torque
- Sliding Block Force
- Starboard Shaft Torque
- Starboard Shaft thrust
- Aft Top Shaft Movement Probe
- Aft Port Shaft Movement Probe
- Forward Port Shaft Movement Probe
- Forward Starboard Shaft Movement Probe
- Starboard Main Servo Differential Oil Pressure
- Starboard Propeller Pitch
- Starboard Shaft Speed and Orientation
- Starboard Rudder Angle
- Ship Speed
- Starboard Engine Fuel Rack

In the 1983 test program, conventional FM analog recording on a 21 channel tape format had been used to acquire the data. This had the advantage of being a relatively simple approach to implement and provided ample recording bandwidth for the data. The disadvantages of the approach included a very limited capability to inspect or analyze the data on-site, poor amplitude resolution and stability normally associated with analog recording and very labour intensive procedures required to locate and reproduce the significant events on the tape during the analysis phase. Some on-site analysis capability had been provided in the form of an eighteen channel ultraviolet (u.v.) oscillograph recorder for displaying the individual channel waveforms in real time, and a waveform analyzer to provide real time spectral analysis of the data.

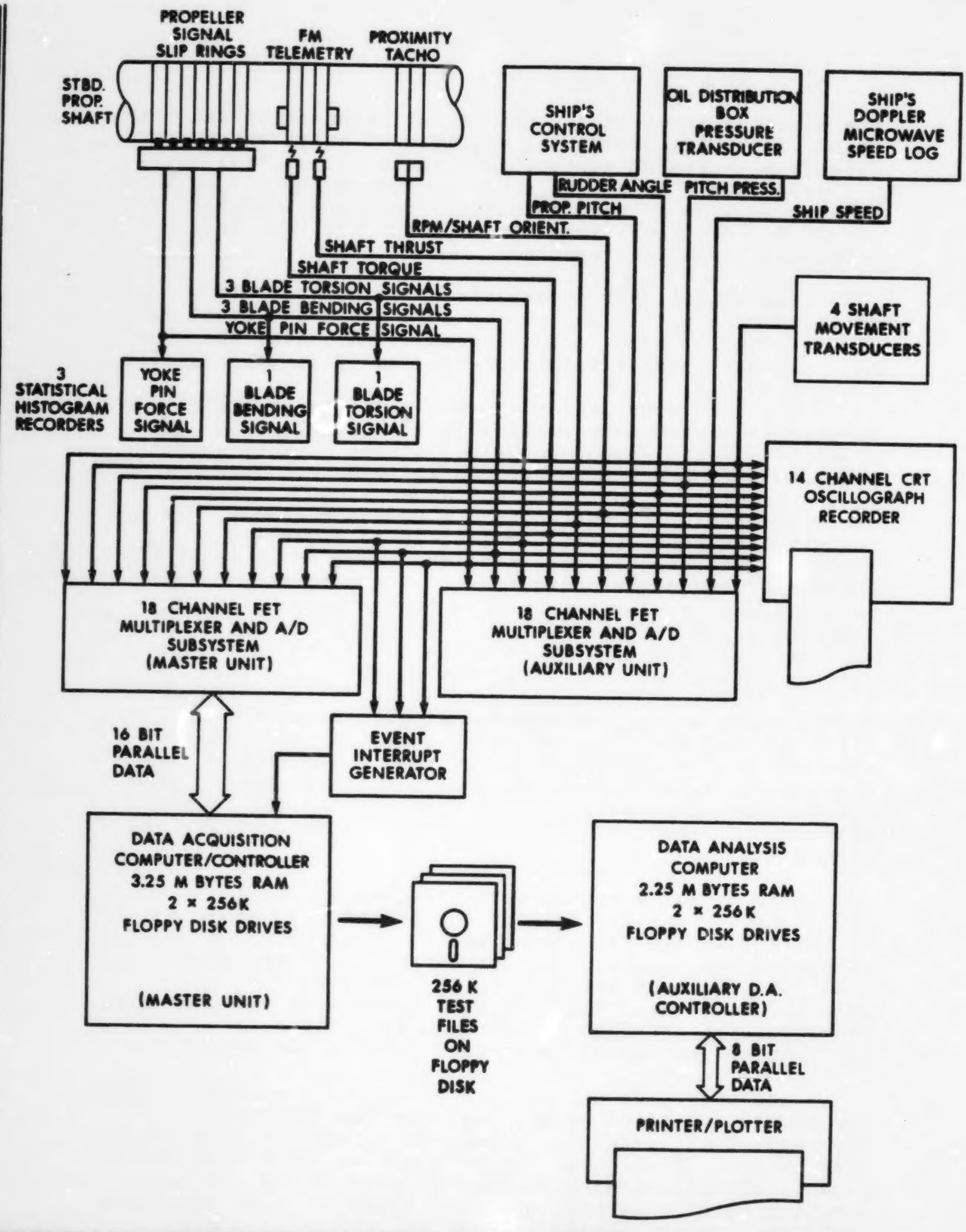
Because of the problems associated with analog recording, CANMAR had been making increasing use of digital data acquisition for shipboard measurements. Initially this was limited to relatively low bandwidth measurements and rather few channels of data, but with the advent of inexpensive super-micro computers supporting very large memory spaces and efficient operating systems for handling input and output of vast amounts of data, the possibility of implementing significant multi-channel dynamic measurement applications in an all-digital system was opened up. As a result of the successful use of such systems in 1983 in ship structural response studies, CANMAR decided to extend this approach for the 1984 propeller blade load program.

The significant advantages of this were: It provided much better and more stable amplitude resolutions of the signals; Much faster access to the data, and; Far more extensive and flexible on-site analysis capabilities.

The data acquisition system specified for this project is depicted schematically in Figure 2.5.1. The system was built around an HP model 9836 desktop computer equipped with 4 Megabytes of central memory. The analog-to-digital subsystem was an HP6940B multi-programmer connected to the HP9836 computer through Hewlett Packard's 16 bit parallel GP-IO interface. The 6940B was selected, rather than the newer model 6942A because of the higher data transfer rate to the controller's central memory made possible by the GP-IO. The high speed interface was not supported by the 6942A and the local memory that could be installed in the 6942A was not sufficient for the extensive buffering required in this application. Equipped with 32 channels of FET switch multiplexing and a high speed analog-to-digital converter, the 6940B was tested at scanning rates up to 27,500 channels per second, storing the readings directly into the central memory of the HP 9836 computer. Beyond this speed occasional readings were lost causing the channel sequence to shift within the data buffer being filled in memory.

The actual scanning rate selected for this application was 1029 readings per second for each channel, or 18522 channels per second total. This provided for somewhat more than ten samples per cycle of the 90 Hz blade torsion mode frequency. The sampling rate was selected after examining the 1983 blade data and comparing the waveforms obtained by sampling at various rates from 100 samples per second up to 2000 samples per second.

The objective of the data acquisition system design was to use the large memory space of the HP9836 to implement a multi-channel transient recorder with a long time window. A circular buffer would be defined in memory capable of holding many seconds of data at the desired sampling rate. The Analogue to Digital (A to D) subsystem would then be programmed to continuously acquire data, filling the buffer and then wrapping around to overwrite it. This would continue indefinitely until significant


PROPELLER SIGNAL SLIP RINGS
FM TELEMETRY
PROXIMITY TACHO
STBD. PROP. SHAFT
SHIP'S CONTROL SYSTEM
OIL DISTRIBUTION BOX PRESSURE TRANSDUCER
SHIP'S DOPPLER MICROWAVE SPEED LOG
RUDDER ANGLE
PITCH PRESS.
PROP. PITCH
SHIP SPEED
RPM/SHAFT ORIENT.
SHAFT THRUST
SHAFT TORQUE
3 BLADE TORSION SIGNALS
3 BLADE BENDING SIGNALS
YOKE PIN FORCE SIGNAL
4 SHAFT MOVEMENT TRANSDUCERS
3 STATISTICAL HISTOGRAM RECORDERS
YOKE PIN FORCE SIGNAL
1 BLADE BENDING SIGNAL
1 BLADE TORSION SIGNAL
14 CHANNEL CRT OSCILLOGRAPH RECORDER
18 CHANNEL FET MULTIPLEXER AND A/D SUBSYSTEM (MASTER UNIT)
18 CHANNEL FET MULTIPLEXER AND A/D SUBSYSTEM (AUXILIARY UNIT)
16 BIT PARALLEL DATA
EVENT INTERRUPT GENERATOR
DATA ACQUISITION COMPUTER/CONTROLLER 3.25 M BYTES RAM 2 × 256K FLOPPY DISK DRIVES (MASTER UNIT)
256 K TEST FILES ON FLOPPY DISK
DATA ANALYSIS COMPUTER 2.25 M BYTES RAM 2 × 256K FLOPPY DISK DRIVES (AUXILIARY D.A. CONTROLLER)
8 BIT PARALLEL DATA
PRINTER/PLOTTER

| | | |
|---|---|---|
| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: PROPELLER BLADE LOAD DATA ACQUISITION SYSTEM<br>FIGURE No. 2·5·1 |

signal excursions associated with ice impacts on the instrumented propeller blade were detected in the input waveforms. After receipt of this "trigger", the data acquisition would continue for a preset length of time to ensure adequate capture of the ice interaction and then the contents of the buffer surrounding the trigger moment would be written out to one of the computer's built-in floppy disk drives to create a permanent record of the event. The scanning of the input signals would then resume until another event was detected.

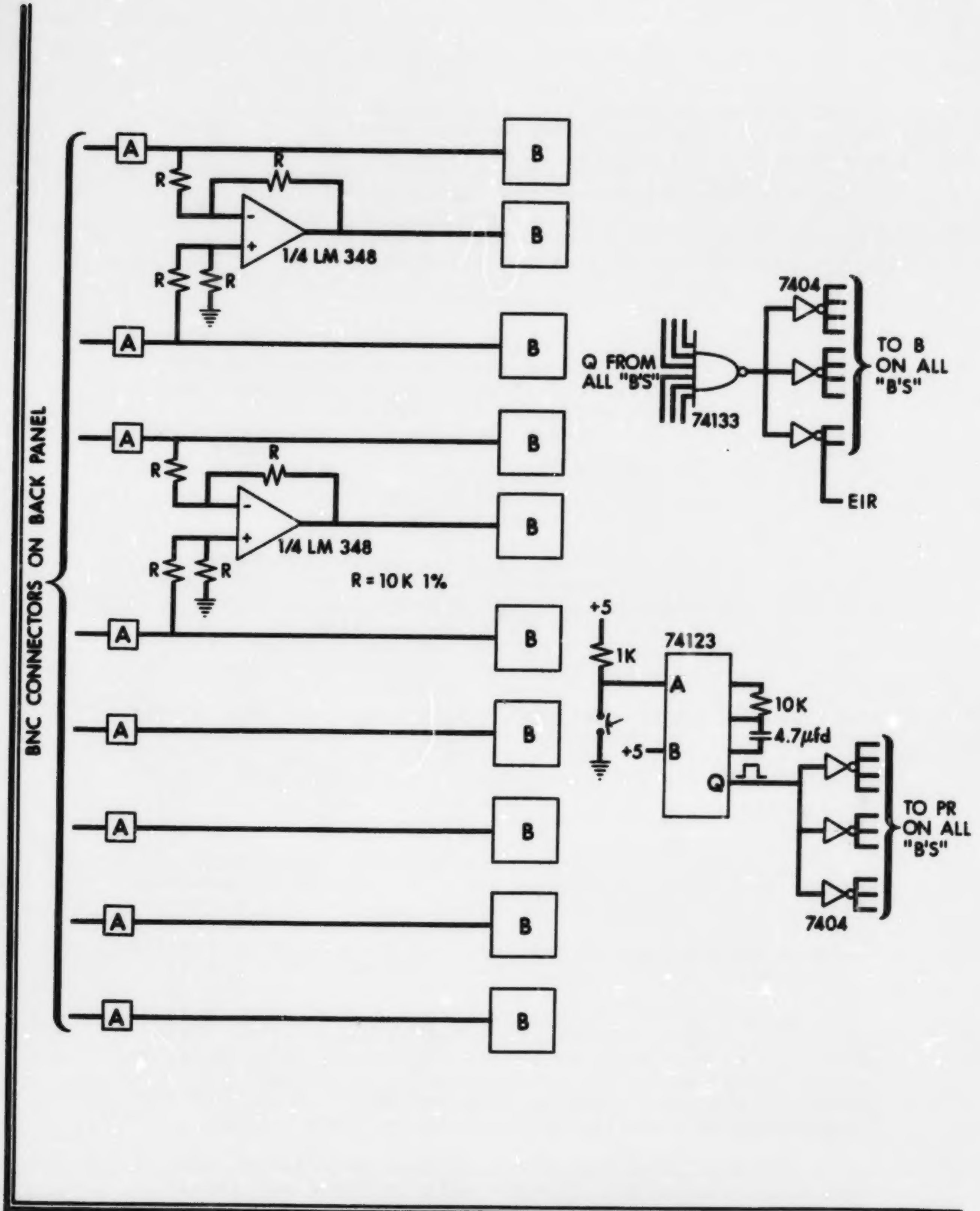
Previous experience with the HP9836 had indicated that at these transfer rates the Central Processing Unit (CPU) would be unable to test more than a very small part of the incoming data stream against trigger criteria, particularly if the software for this task was written in a high level language. In order to provide for more flexible and reliable event detection it was decided to perform this function using analogue processing of the blade, sliding block and shaft torque signals.

An analogue event detector was built (see Figures 2.5.2 to 2.5.4 for schematics) to accept these signals as inputs: To bandwidth limit the signals and prevent triggering on very slow or very fast changes in signal level that were not due to blade mechanical response to impact; To rectify the signals so that triggering was independent of the sense of the excursion, and; To continuously compare the result with preset trigger levels for each channel. When any one of the channels exceeded its trigger setpoint the unit sent an interrupt to the CPU of the HP9836 via a dedicated GP-IO interface and loaded the interface data lines with a code to tell the CPU which input or inputs had caused the trigger.

In addition to testing the analogue inputs against trigger setpoints, provision was also made to compare the differences of two pairs of channels against setpoints so that triggering for more restricted classes of events could be implemented if desired (see discussion in Section 3.1 regarding calculation of Force and Bending Moments).

By performing the event detection continuously as an analogue function, all of the incoming data stream could be processed for event detection and all of the available processing power in the HP9836 could be allocated to servicing the data transfer from the multi-programmer and to maintaining an orderly status in the data buffer.

The data acquisition system used to measure long term shaft statistics is dealt with in the final report.

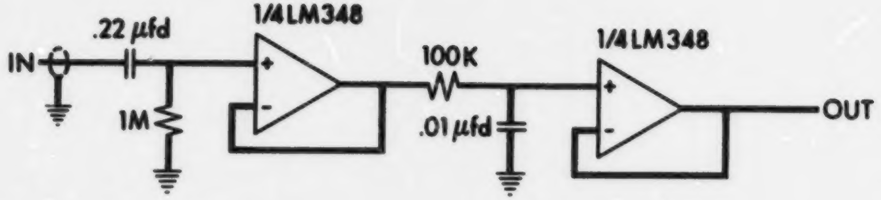

BNC CONNECTORS ON BACK PANEL
A
B
R
1/4 LM 348
R = 10K 1%
Q FROM ALL "B'S"
74133
7404
TO B ON ALL "B'S"
EIR
+5
1K
74123
A
B
Q
+5
10K
4.7µfd
TO PR ON ALL "B'S"
7404

**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE-PROPELLER INTERACTION PARAMETERS**

TITLE: TRIGGER CIRCUIT
OVERALL CIRCUIT LAYOUT

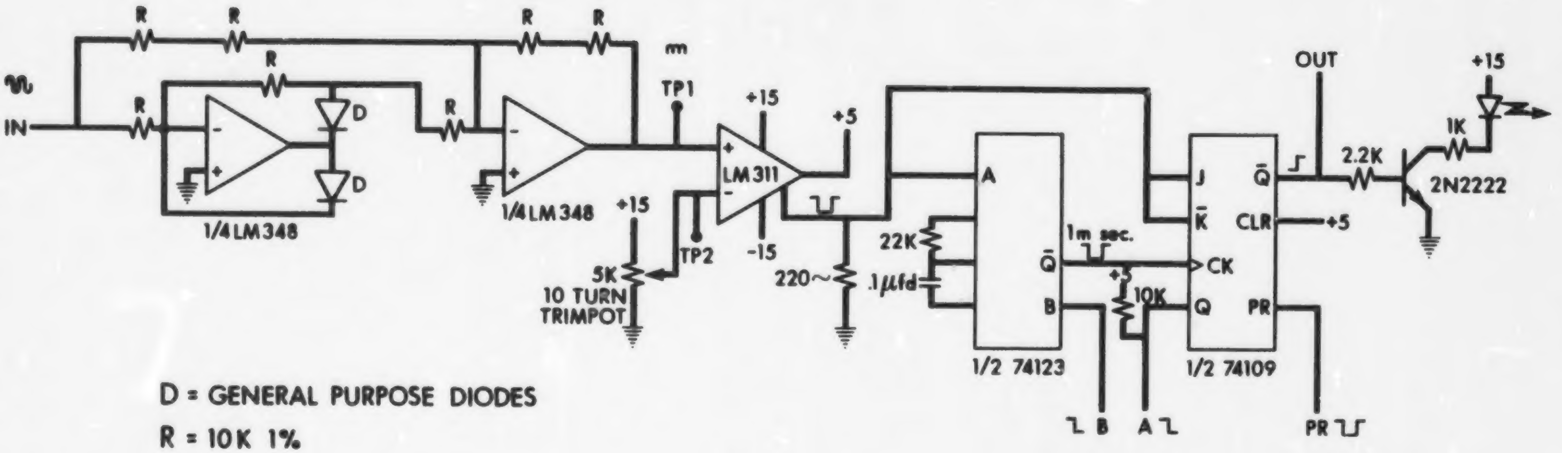
FIGURE No. 2·5·2


IN
.22 µfd
1M
1/4LM348
100K
.01 µfd
1/4LM348
OUT

$f_L \approx 0.4$ Hz
$f_H \approx 250$ Hz

BANDPASS

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE-PROPELLER<br>INTERACTION PARAMETERS | TITLE: TRIGGER CIRCUIT<br>INPUT BUFFERING AND FILTERING<br>CIRCUIT "A" |
| | | FIGURE No. 2·5·3 |


IN
R
R
R
R
D
D
1/4LM348
R
R
R
1/4LM348
m
TP1
+15
LM311
+15
-15
TP2
+15
5K
10 TURN
TRIMPOT
+5
220~
22K
.1μfd
A
Q̄
B
1/2 74123
1m sec.
+5
10K
⅂ B
A ⅂
J
K̄
CK
Q
Q̄
CLR
PR
+5
1/2 74109
PR
OUT
2.2K
1K
+15
2N2222

D = GENERAL PURPOSE DIODES

R = 10K 1%

CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE-PROPELLER
INTERACTION PARAMETERS

TITLE: TRIGGER CIRCUIT
RECTIFICATION, ALARMING AND LATCHING
CIRCUIT "B"

FIGURE No. 2·5·4

# 3. CALIBRATION OF THE PROPELLER BLADE

## 3.1 Accuracy of the Influence Coefficient Method

A major component of the test program was to measure the force location and magnitude plus the spindle torque and bending moment resulting from ice/propeller interaction. To this aim, a set of six strain gauge bridges were mounted within recesses near the root of the propeller blade. Three of the bridges responded mainly to out-of-plane blade bending and three, mainly to torsion around the longitudinal axis of the blade.

In order to relate any measured set of strain gauge outputs to the loading of the blade, the method of influence coefficients was used (Ref 3.1). This methodology was developed by the Technical Research Centre of Finland Ship Laboratories as part of the 1983 test program. For the 1984 program, considerable additional work was performed on investigation and description of the errors associated with the analytical approach.

In preparation for the physical calibration of the propeller blade extensive investigations were performed on the accuracy and limitations of the influence coefficient approach. The emphasis was on determining what accuracy could be expected utilizing data from the six strain gauge bridges and what factors affected the accuracy and hence what would be a suitable calibration scheme.

The data used in the investigations was the laboratory calibration data obtained by the Technical Research Centre of Finland Ship Laboratory (Ref 1.5). While the laboratory data was not used directly in the 1984 test phase due to differences in the blade support condition in the laboratory and in the field, the data was an excellent source for the investigation of accuracy.

The calibration data collected during the current project is given in Section 3.2 together with graphs and figures indicating the prediction accuracy of the current installation.

### 3.1.1 Influence Coefficient Method

Assuming that the material responds linearly to the applied loading function, then the relationship between the structural response and the applied loading condition can be written in the following matrix format:

$$(g) = [R] * (F) \qquad \text{eq: 3.1.1}$$

where (g) is the response vector
(F) is the loading vector
and [R] is the transfer matrix

By using standard matrix manipulations, equation 3.1.1 can be transformed to give

$$(F) = [R]^{-1} * (g) \qquad \text{eq: 3.1.2}$$

If we let $[A] = [R]^{-1}$
then $(F) = [A] * (g)$ eq: 3.1.3

Equation 3.1.3 provides the way of calculating the loading condition from the structural response. In our case (F) consists of force, bending moments, spindle torque, and (g) the six strain gauge readings.

The major unknown is the value of elements of the [A] matrix. These elements can be calculated from first principles from the system geometry using techniques such as Finite Element Modelling (Ref 3.2). The complex geometry of the blade, its support, the machined recesses and access holes for gauging make this approach inappropriate for high accuracy. Alternatively, the elements of [A] can be determined from a physical calibration procedure. In essence it consists of applying a known load to the blade at a known location and orientation and then recording the strain gauge readings for each loading condition. The data is then mathematically processed to give values of the elements of [A].

### 3.1.2 Definitions

- Out-of-plane bending moment (M): The plane is that containing the lower gauges mounted at the relative radius $r/R = 0.47$. Thus the out-of-plane bending moment is the product of the component of the force normal to this plane, times the distance to the blade root at relative radius $r/R = 0.37$.

- In-plane bending moment (Mp): The plane is the same plane as used to determine the out-of-plane bending moment. The in-plane bending moment is also the moment which exists at the root of the blade at $r/R = 0.37$. Thus, the in-plane bending moment is the component of the force in the plane of the blade at $r/R = 0.47$ times the distance to the root of the blade.

- Out-of-plane force (F): The component of the force normal to the r/R = 0.47 plane.

- Spindle Torque (T): The product of out-of-plane force times the perpendicular distance to the blade center line, plus (or minus) the in-plane force times its perpendicular distance from the blade centerlne.

- Location of the load: The radial and circumferential locations of the load are given by:

  Height = M/F    eq: 3.1.4

  Circumferential position = T/F    eq: 3.1.5

The gauges are labelled $g_1$ to $g_6$ and represent:

$g_1$ = Bending gauge located at blade center
$g_2$ = Torsion gauge located towards trailing edge
$g_3$ = Bending gauge located towards leading edge
$g_4$ = Torsion gauge located at blade center
$g_5$ = Bending gauge located towards trailing edge
$g_6$ = Torsion gauge located towards leading edge

$$(g) = \begin{vmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \\ g_5 \\ g_6 \end{vmatrix}$$

$$(F) = \begin{vmatrix} Mp \\ F \\ M \\ T \end{vmatrix}$$

$$[A] = \begin{vmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} \end{vmatrix}$$

### 3.1.3 Calculation of the Elements of [A]

If we look at the defining equation 3.1.3, we can write out the expression for one row of the matrix. For the case of out-of-plane bending moment M we obtain:

$$m = A_{31}*g_1 + A_{32}*g_2 + A_{33}*g_3 + A_{34}*g_4 + A_{35}*g_5 + A_{36}*g_6$$

The bending moment is thus simply a linear sum of the gauge outputs with weighting factors $A_{31}....A_{36}$. A similar relationships hold for the other rows of the matrix (Mp, T and F).

For each calibration test, one has a known value of M and the six strain gauge outputs. If one has six independent calibration points from various locations on the blade, one can solve for the $A_{31}....A_{36}$. Thus in principle, one only needs six calibration tests in order to arrive at an $A_{31}...A_{36}$ and the same six tests will also provide [A] matrix elements for Mp, F and T. These [A] values could then be used to predict the loading condition of the blade from the actual field collected strain gauge readings. While the fit will be exact if the unknown load was at one of those six loading locations, there is no understanding of how accurate the fit or prediction is at other locations. The accuracy of the fit can be estimated by utilizing calibration data from other locations and comparing predicted with actual loads. Again, the accuracy of the fit between the loading test points is not known. However, if one assumes that the fit is a smoothly varying function, then interpolation between calibration test points will suffice. The particular value of the $A_{31}...A_{36}$ obtained will depend upon which subset of the calibration data points is used and hence the global accuracy of the fit will depend on which six calibration points are selected and in which part of the blade the calibration data points are located. If there are only ten calibration points, the number of different possible combinations of calibration points is approximately five thousand. An alternative approach is to use all calibration data points and to calculate the $A_{31}..A_{36}$ by a multiple linear regression technique (Ref 3.3). This will automatically provide the best fit between the predicted values and the actual measured loading values averaged over the locations of the calibration points.

Given the complex propeller blade geometry, there is no guarantee that six strain gauges located near the base of the blade can accurately predict the force, location etc. of the load. The greater the number of gauges (at separate locations), the better the fit will likely be. So given only six (or less) gauges, a perfect fit may not occur over the whole blade surface. In the multiple linear regression technique the best average fit will be obtained, therefore, so if in one part of the blade the fit is poor, it will affect the fit at other parts of the blade. One may be able to improve the fit at the leading edge for example, by using calibration data points from only the leading edge of the blade. In general, the fit at the parts of the blade which were not represented will, on average, be worse than the fit using data from all parts of the blade.

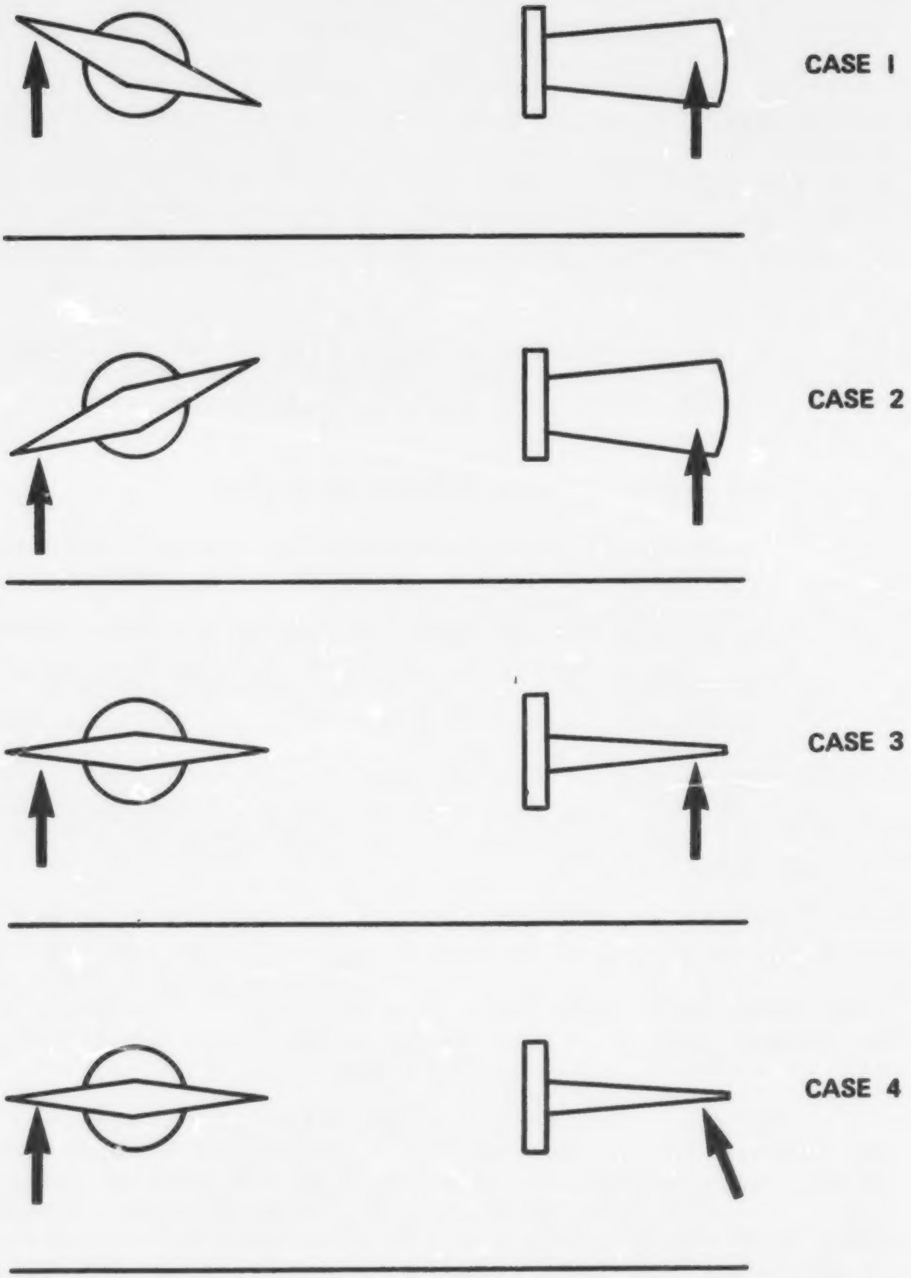
We shall now present some results of the linear regression approach (which was developed by Canmar as part of the current program) to investigate the influence coefficient method.

The major factors investigated were:

- Accuracy of in-plane bending moment determination.
- Accuracy of out-of-plane bending moment determination.
- Accuracy of out-of-plane force determination.
- Accuracy of spindle torque determination.
- Accuracy of load location determination.
- Accuracy of determinations 1. to 5. as a function of loading orientation.
- Accuracy of determinations 1. to 5. as a function of the spatial distribution of loading points.
- Effect on accuracy of utilizing only 5 or 4 gauge signals.

In the static calibration process, a load was applied to a number of locations on the blade. At each location up to four load orientations were tested. The four loading directions are illustrated in Figure 3.1.1. Different load directions, as illustrated in Figure 3.1.1, are referred to as Case 1 to Case 4.

In the calculation of the [A] matrix elements one can choose to include all data points or a subset of the data. For example, only data from the leading half of the blade or only data from Case 1. Once the [A] elements have been calculated, the fit will be evaluated by comparing the actual loading condition with the predicted loading condition at each and every load point, not just those used in the calculation of the [A] elements.


CASE 1
CASE 2
CASE 3
CASE 4

CANADIAN
MARINE
DRILLING
LIMITED

MEASURE OF ICE
PROPELLER INTERACTIONS

TITLE:
LOADING DIRECTIONS DURING
LABORATORY CALIBRATION, 1983 TESTS

FIGURE No. 3.1.1

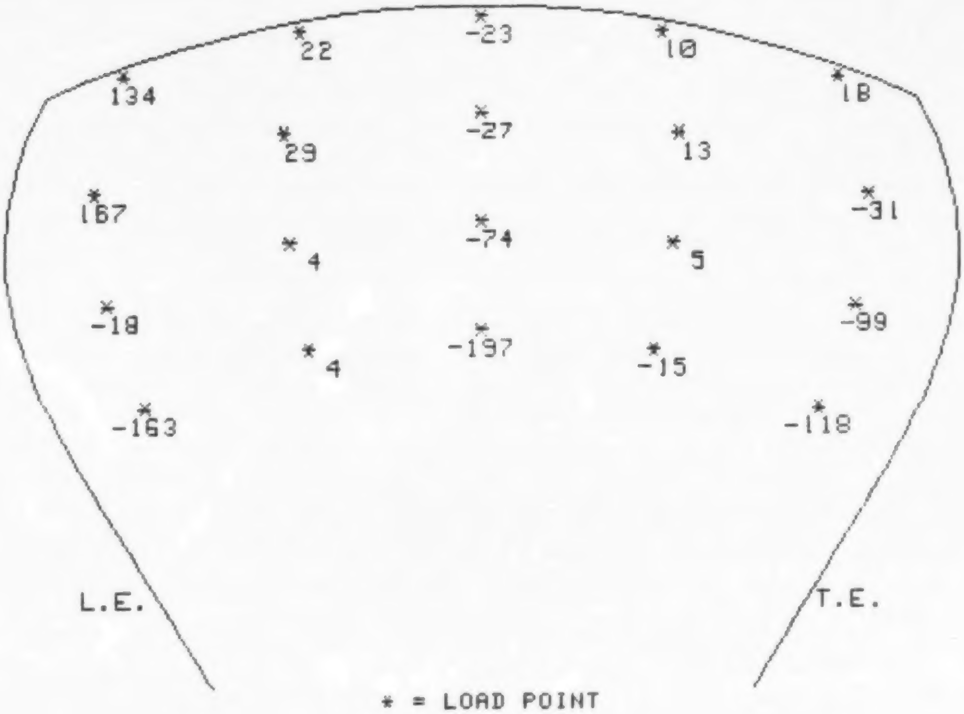
The computer program written to calculate the [A] elements and to estimate the accuracy of the approach is given in Appendix D. Also, the program listing for creating a data file suitable for a matrix test from calibration data is included. Figure 3.1.2 to 3.1.6 show data obtained by using loading locations common to Cases 1 to 4 and the comparison displayed for Case 3. The figures show the fit for in-plane bending, out-of-plane bending, out-of-plane force, spindle torque and load location. The loading points are marked by crosses and the number adjacent is the percentage difference between predicted and actual loading. For the load location, the predicted location is at the end of the line emanating from a cross.

If we look at Figure 3.1.3 for example, given for out-of-plane force, Case 3 refers to essentially normal loading to the blade (see Figure 3.1.1). Since the blade has a twist to it, approximately 17 degrees between the root and the tip, we have defined out-of-plane to be normal to the blade plane at relative radius $r/R = 0.47$. The lower row of points in Figure 3.1.3 corresponds to relative radius $r/R = 0.70$. From this figure, one can see that the accuracy of the fit is not constant over the blade surface. (As an aid to the reader the 'Average Difference' is the average % difference, ignoring sign.) Similar behaviour is observed for spindle torque and an out-of-plane bending moment where the fit is poorest towards the root of the propeller blade.

The values given in Figures 3.1.2 to 3.1.5 can be explained in the following way. Three gauges respond to mainly bending moment and three gauges to mainly torsion of the blade, hence the output of any one gauge is strongly correlated with the quantities, of out-of-plane bending moment or spindle torque.

The out-of-plane force on the other hand is related to the difference in bending moments and can be demonstrated as follows. Assume we have a clamped-free beam with bending moment gauges located at a distance $d_1$ and $d_2$ from the free end. Let the output of the gauges be $M_1$ and $M_2$ and a load, F applied to the free end. Then we can write:

$$M_1 = d_1 * F$$
$$M_2 = d_2 * F$$

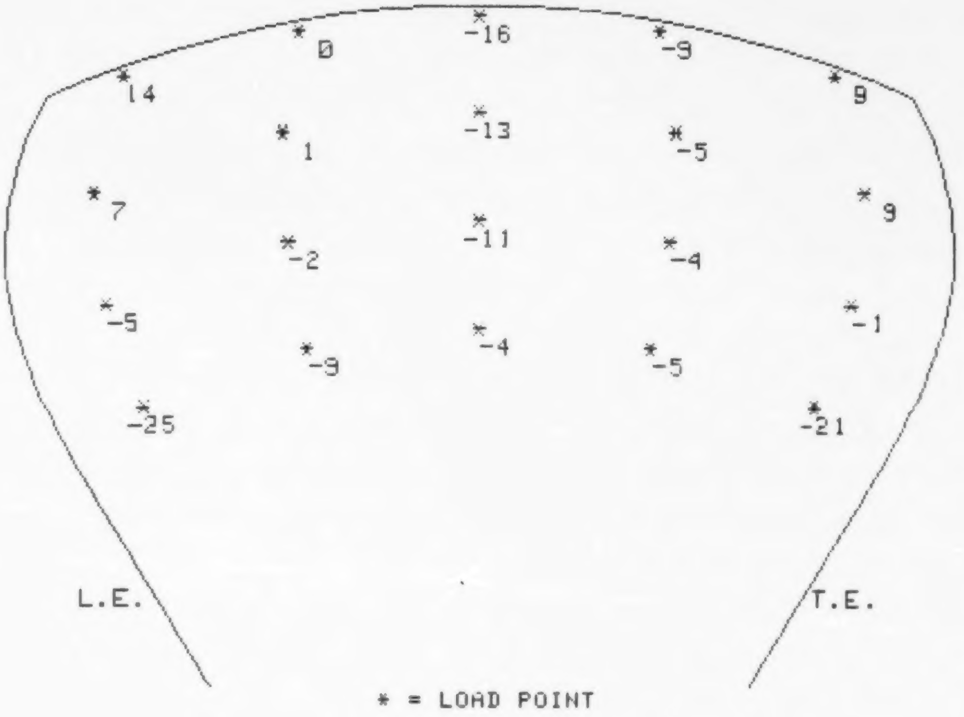


**ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS**

13 APR 1984 14:35:51
DATA - IN-PLANE BENDING MOMENT - % DIFFERENCE
CASE - 3
AVERAGE DIFFERENCE - 58%

ONLY POINTS COMMON TO CASES 1 TO 4

| | | |
|---|---|---|
| CANADIAN MARINE DRILLING LIMITED | MEASURE OF ICE PROPELLER INTERACTIONS | TITLE: IN-PLANE BENDING MOMENT (% DIFFERENCE) CASE 3 |
| | | FIGURE No. 3.1.2 |

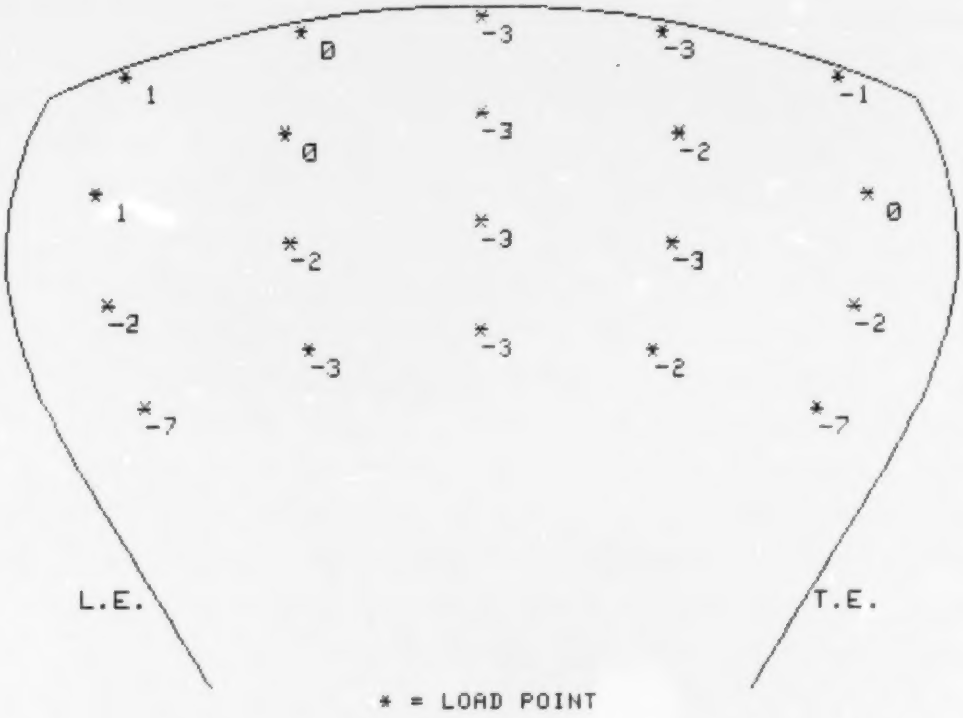


## ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS

**13 APR 1984 14:37:29**
**DATA - OUT-OF-PLANE FORCE - % DIFFERENCE**
**CASE - 3**
**AVERAGE DIFFERENCE - 8%**

**ONLY POINTS COMMON TO CASES 1 TO 4**

| | | |
|---|---|---|
| CANADIAN MARINE DRILLING LIMITED | MEASURE OF ICE PROPELLER INTERACTIONS | TITLE: OUT-OF-PLANE FORCE (% DIFFERENCE) CASE 3 |
| | | FIGURE No. 3.1.3 |

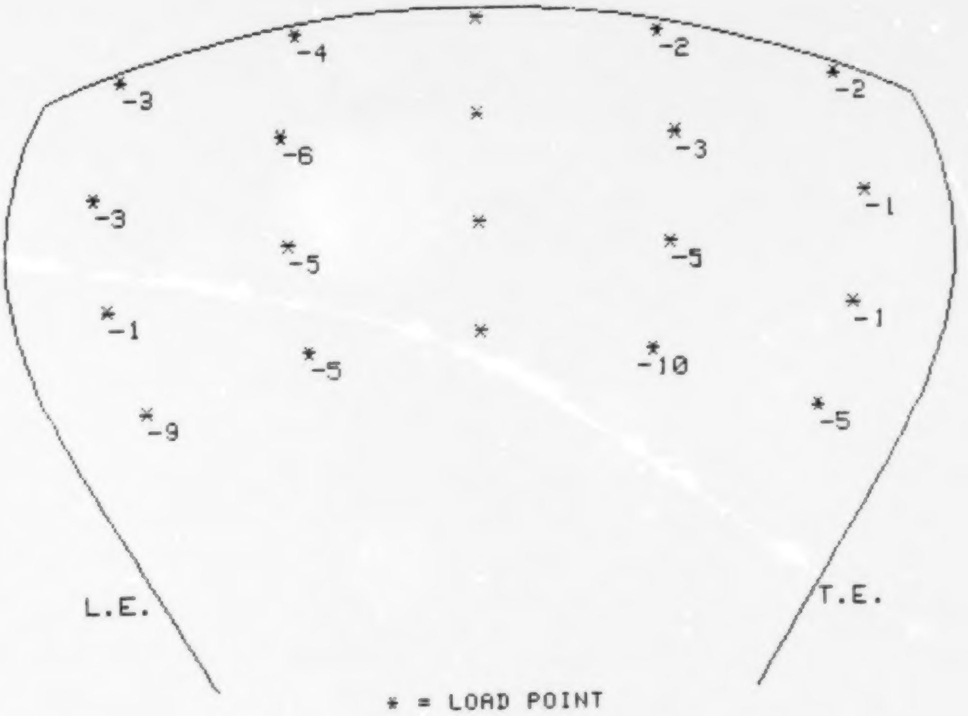


**ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS**

13 APR 1984 14:39:10
DATA - OUT-OF-PLANE BENDING MOMENT - % DIFFERENCE
CASE - 3
AVERAGE DIFFERENCE - 2%

ONLY POINTS COMMON TO CASES 1 TO 4

| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASURE OF ICE PROPELLER INTERACTIONS** | **TITLE:**<br>**OUT-OF-PLANE BENDING MOMENT (% DIFFERENCE) CASE 3** |
| | | **FIGURE No. 3.1.4** |


*
*-4
*-2
*-3
*-2
*
*-6
*-3
*-3
*-1
*
*-5
*-5
*-1
*
*-1
*-5
*-10
*-9
*-5
L.E.
T.E.
* = LOAD POINT

**ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS**

**13 APR 1984 14:40:52**
**DATA - SPINDLE TORQUE - % DIFFERENCE**
**CASE - 3**
**AVERAGE DIFFERENCE - 4%**

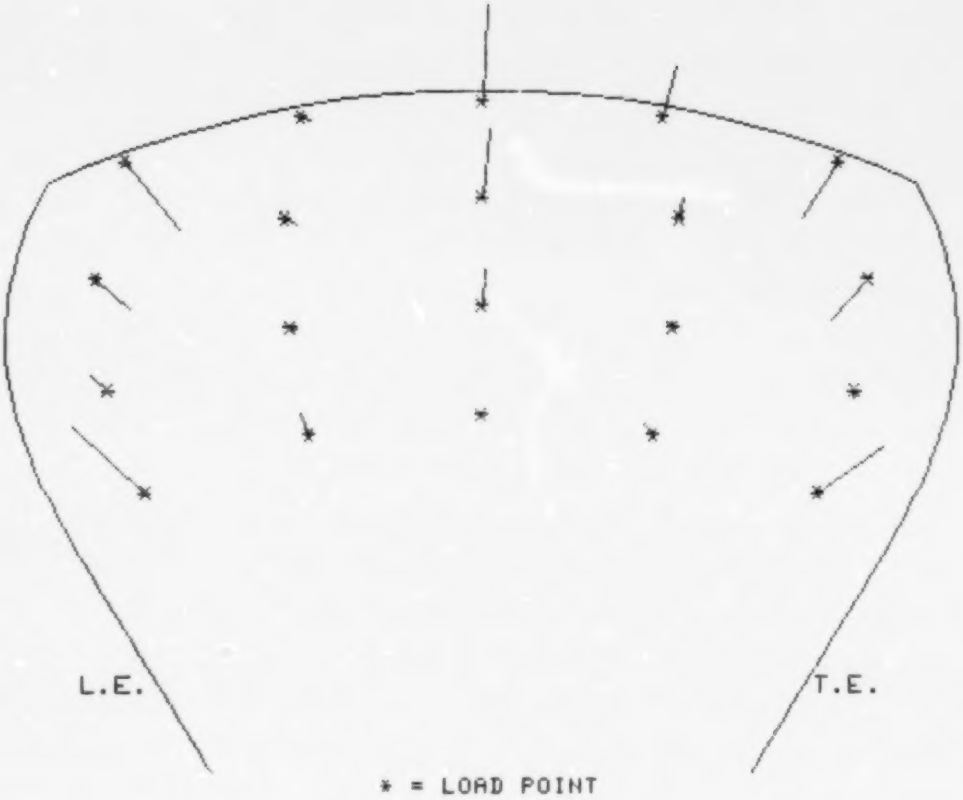
**ONLY POINTS COMMON TO CASES 1 TO 4**

**CANADIAN**
**MARINE**
**DRILLING**
**LIMITED**

**MEASURE OF ICE**
**PROPELLER INTERACTIONS**

**TITLE:** **SPINDLE TORQUE**
**(% DIFFERENCE) CASE 3**

**FIGURE No. 3.1.5**



**ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS**

13 APR 1984 14:42:28
DATA - PREDICTED LOCATION VS. ACTUAL LOCATION (*)
CASE - 3
AVERAGE DIFFERENCE - 56mm

ONLY POINTS COMMON TO CASES 1 TO 4

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASURE OF ICE<br>PROPELLER INTERACTIONS | TITLE: PREDICTED LOCATION VS. ACTUAL LOCATION CASE 3<br>FIGURE No. 3.1.6 |

Let the separation between the gauges $d_1 - d_2 = \Delta$

then $M_1 = (d_2 + \Delta) F$,

and $M_1 = M_2 + \Delta F$

or by rearranging

$F = (M_1 - M_2)/\Delta$

Hence this equation demonstrates that the magnitude of the force is related to the difference in bending moment gauge readings situated at different radial distances on the blade, in this case relative radii 0.47 and 0.60. As the separation between gauges decreases, the difference between $M_1$ and $M_2$ decreases and hence F is the ratio of two small qualities. Thus the error in the estimation of F is greater than the error in $M_1$ and $M_2$. By using the propagation of errors technique (Ref 3.4) we can write the relative error in F as:

$$\sigma F/F = (\sigma^2 M_1 + \sigma^2 M_2)^{1/2}/(M_1 - M_2)$$

Where $\sigma F$, $\sigma M_1$, $\sigma M_2$ are the standard errors in F, $M_1$, and $M_2$ respectively.

Putting in reasonable values for these quantities and if $\sigma M_1/M_1 = 5\%$ then $\sigma F/M_1 = 25\%$, in agreement with the observed values.

The accuracy of the in-plane bending moment is expected to be poor because of the relatively small strains produced by a unit load applied in the in-plane direction compared with the out-of-plane direction. Calculations for the case of in-plane bending moment were nevertheless carried out.

Figure 3.1.6 shows the predicted location of the load, the location being calculated as the ratio of M/F and T/F for the radial and circumferential locations. It can be seen that near the blade tip this particular [A] matrix over estimates the radial location of the load but otherwise the accuracy of the location is considered to be good. The scale of accuracy for location is that it should be smaller than the dimensions of a typical contact zone between the ice and the blade. Since typical block dimensions are the order of 50 cm to 150 cm, accuracies in the order of 60 mm are excellent.

The effect of load orientation on the fit is displayed in Figures 3.1.7 to 3.1.10 for the case of out-of-plane force. In these figures, the same set of data was used in the calculation of [A] and the fit for different loading directions is displayed. By inspection of these figures, one can see that the effect of changing the load direction by approximately 35° can result in changes in fit of the order to 10% near the leading edge. As the loading direction is generally not known with any great accuracy, this will result in an additional level of error in the determination of the fitted quantities.

In light of the instrumentation failures experienced in the 1983 test program, the effect on prediction accuracy of having only 5 or 4 gauges working was investigated. The data is summarized in Table 3.1.1. In this table the relative accuracy is given as a function of the number of gauges included in the fit. For this data the [A] matrix was calculated using 6, 5 or 4 active gauges and the fit accuracy calculated using 6, 5 or 4 gauges. It is thus the best fit given the number of active gauges. As expected, the accuracy decreased as the number of gauge signals was reduced. The data given in Table 3.1.1 is from inspection of Case 3 data and not an average over all loading directions.

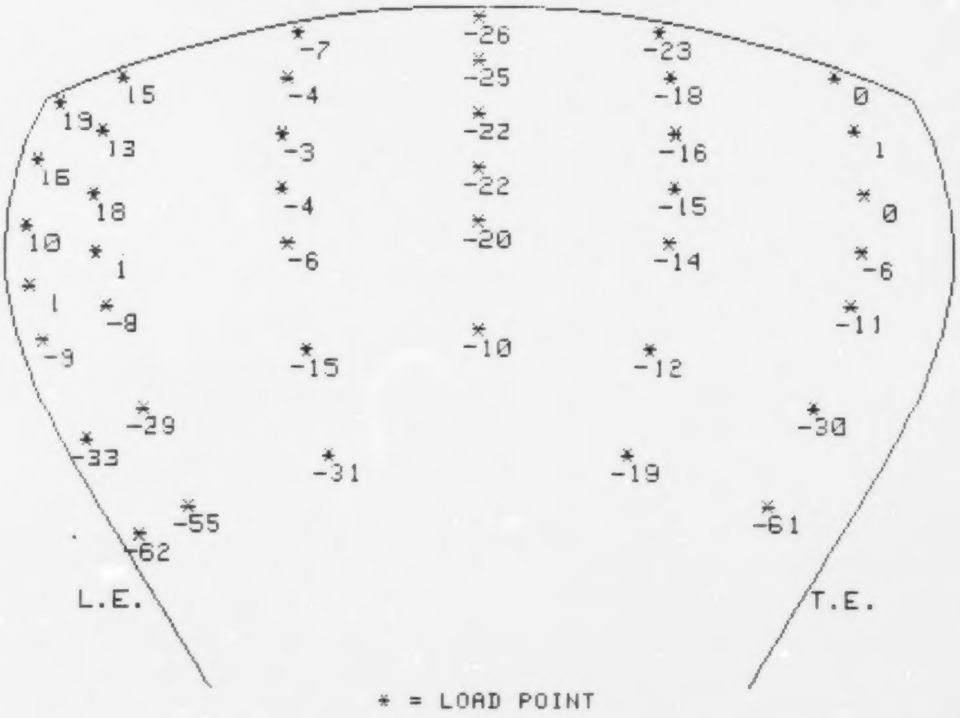
In Table 3.1.2 data is presented for a representative [A] matrix. Note that these values cannot be used in the 1984 data analysis but can be used to determine which gauge most strongly affects the predicted values of (F). For example, M is strongly dependent on the bending gauges rather than on the torsion gauges, and T is most dependent on gauges off of the blade center line.

The conclusions from the analysis performed and the data presented here are as follows:

- For the accuracy of implementation of the Influence Coefficient Method:

The data given here is an average over all the five loading directions. Hence the accuracy given is greater than that given in Table 3.1.1 for the row with six active gauges.

| | Average Accuracy Over Blade Surface | Maximum Difference in leading half of the blade at relative radius greater than 0.7 |
|---|---|---|
| $M_p$ (%) | 80 | 300 |
| F (%) | 15 | 30 |
| M (%) | 5 | 20 |
| T (%) | 10 | 30 |
| location (mm) | 120 | 250 |

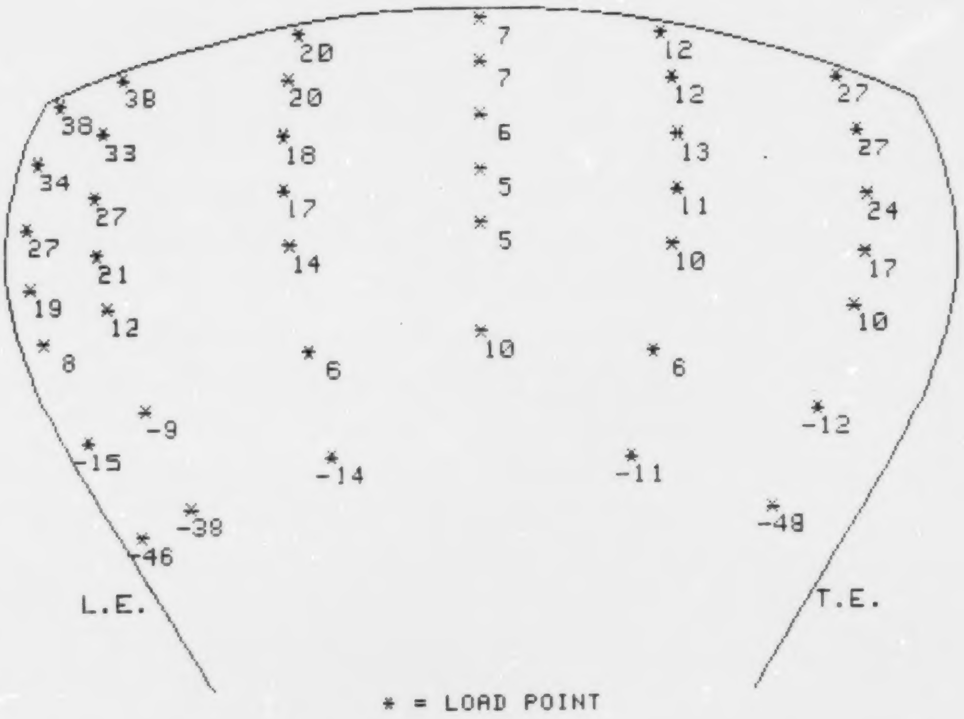


**ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS**

13 APR 1984 14:36:43
DATA - OUT-OF-PLANE FORCE - % DIFFERENCE
CASE - 1
AVERAGE DIFFERENCE - 17%

ONLY POINTS COMMON TO CASES 1 TO 4

| CANMAR<br>CANADIAN MARINE DRILLING LIMITED | MEASURE OF ICE PROPELLER INTERACTIONS | TITLE: OUT-OF-PLANE FORCE (% DIFFERENCE) CASE 1<br>FIGURE No. 3.1.7 |
|---|---|---|

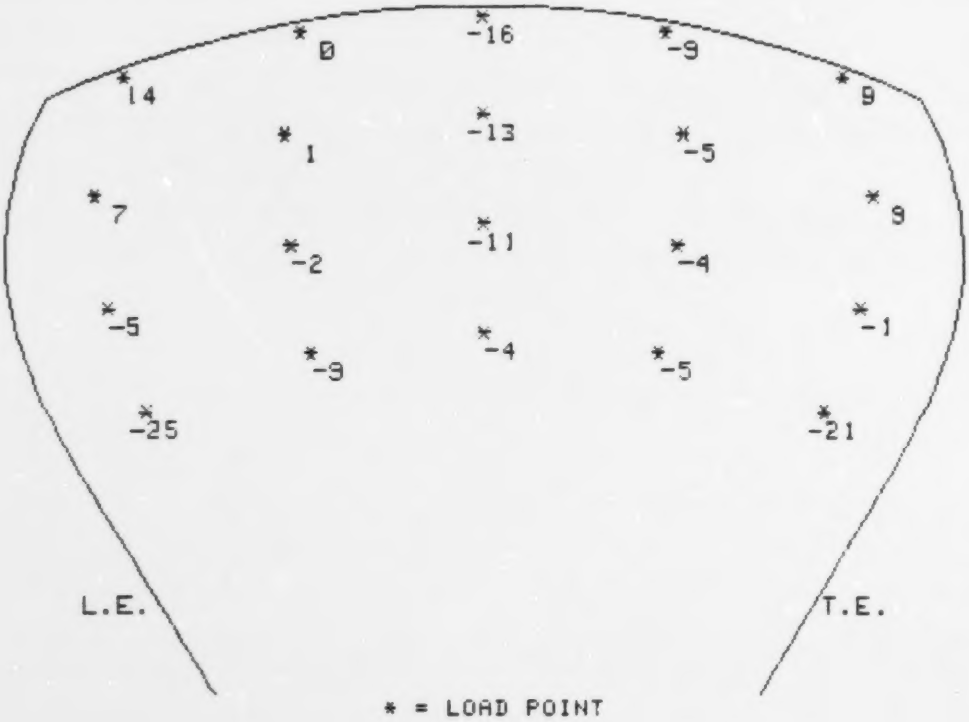


**ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS**

**13 APR 1984 14:37:07**
**DATA - OUT-OF-PLANE FORCE - % DIFFERENCE**
**CASE - 2**
**AVERAGE DIFFERENCE - 18%**

**ONLY POINTS COMMON TO CASES 1 TO 4**

| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASURE OF ICE<br>PROPELLER INTERACTIONS | TITLE: OUT-OF-PLANE FORCE (% DIFFERENCE) CASE 2<br>FIGURE No. 3.1.8 |
|---|---|---|

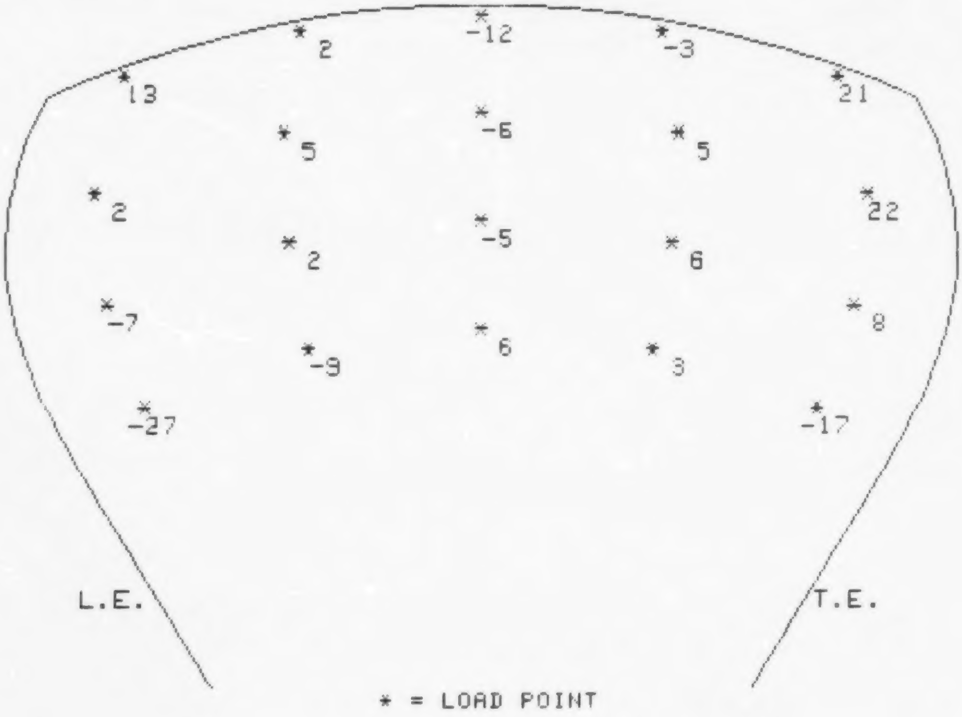


**ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS**

**13 APR 1984 14:37:29**
**DATA - OUT-OF-PLANE FORCE - % DIFFERENCE**
**CASE - 3**
**AVERAGE DIFFERENCE - 8%**

**ONLY POINTS COMMON TO CASES 1 TO 4**

| CANMAR<br>CANADIAN MARINE DRILLING LIMITED | MEASURE OF ICE PROPELLER INTERACTIONS | TITLE: OUT-OF-PLANE FORCE (% DIFFERENCE) CASE 3<br>FIGURE No. 3.1.9 |
|---|---|---|


2
-12
-3
13
21
5
-6
5
2
22
-5
2
6
-7
8
-9
6
3
-27
-17
L.E.
T.E.
* = LOAD POINT

## ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS

13 APR 1984 14:37:52
DATA - OUT-OF-PLANE FORCE - % DIFFERENCE
CASE - 4
AVERAGE DIFFERENCE - 9%

ONLY POINTS COMMON TO CASES 1 TO 4

| CANADIAN MARINE DRILLING LIMITED | MEASURE OF ICE PROPELLER INTERACTIONS | TITLE: OUT-OF-PLANE FORCE (% DIFFERENCE) CASE 4<br>FIGURE No. 3.1.10 |
|---|---|---|

All data used in calculation of [A]. Average accuracy over the whole of the blade.

| | Mp(%) | F(%) | M(%) | T(%) | location (mm) |
|---|---|---|---|---|---|
| 6 gauges | 71 | 9 | 2 | 5 | 62 |
| 5 gauges* | 83 | 10 | 3 | 7 | 70 |
| 4 gauges+ | 70 | 13 | 4 | 13 | 97 |

* average of six examples

+ average of three examples each with 2 torsion & 2 bending gauges

**TITLE: ESTIMATED RELATIVE PREDICTION ACCURACY AS A FUNCTION OF NUMBER OF STRAIN GAUGE SIGNALS**

**TABLE 3.1.1**

|  | $g_1$ | $g_2$ | $g_3$ | $g_4$ | $g_5$ | $g_6$ |
|---|---|---|---|---|---|---|
| Mp | $-1.137*10^{-2}$ | $-7.162*10^{-2}$ | $+2.544*10^{-1}$ | $-1.119*10^{-1}$ | $-2.767*10^{-1}$ | $-7.361*10^{-2}$ |
| F | $-8.151*10^{-2}$ | $-1.282*10^{-2}$ | $+5.751*10^{-3}$ | $-2.580*10^{-2}$ | $-1.429*10^{-1}$ | $-3.162*10^{-2}$ |
| M | $-1.117*10^{-2}$ | $-2.038*10^{-3}$ | $-1.478*10^{-2}$ | $-1.505*10^{-3}$ | $-3.217*10^{-2}$ | $-3.903*10^{-3}$ |
| T | $-1.887*10^{-3}$ | $-3.552*10^{-2}$ | $-3.416*10^{-2}$ | $-5.836*10^{-3}$ | $-3.575*10^{-2}$ | $-3.120*10^{-2}$ |

Units F - kN
Mp, M, T - kN.m
$g_1 \cdots g_6$ - mV

$g_1$ = center bending
$g_2$ = trailing edge torsion
$g_3$ = leading edge bending
$g_4$ = center torsion
$g_5$ = trailing edge bending
$g_6$ = leading edge torsion

Mp = In-plane bending moment
F = Out-of-plane force
M = Out-of-plane bending moment
T = Spindle torque

| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: REPRESENTATIVE (A) MATRIX ELEMENTS (ALL DATA USED) |
|---|---|---|
|  |  | TABLE 3.1.2 |

The method provides acceptable accuracy for F, M, T and location but does not predict the in-plane bending moment (Mp) with acceptable accuracy.

- Using all the data in the calculation of [A], the accuracy of the fit decreases as the load location approaches the blade root.
- The direction of the applied load is a significant parameter in terms of prediction accuracy. However, the direction of the load will not be known with certainty.
- Acceptable accuracy is maintained even with only 4 gauges included in the calculation of the out-of-plane bending moment, out-of-plane force, spindle torque and load location.

### 3.1.4 Static Versus Dynamic Analysis

The influence coefficient approach as described is a static or quasi-static analysis technique in which the response of the structure is directly proportional to the applied load at that instant in time. Inertial effects are excluded and no account is taken of structural vibrations.

We shall make an estimate of the range of applicability of a quasi-static approach by modelling the propeller blade as a single degree of freedom oscillator without damping and having natural period $\tau$. From Ref 3.1, the response of the oscillator to a half sine forcing function, F, is within 20% of the response to an infinitely slowly varying load, provided the duration (t) of the input forcing function is greater than 2.2 times the natural period $\tau$.

From data obtained in 1983, the period of natural frequencies for blade bending and blade torsion are approximately 60 Hz and 90 Hz respectively when the blade is in water. By using these frequencies and the fact that the nominal shaft speed is 209 rpm, we can express the critical impact duration in terms of degrees of rotation of the blade. For blade bending and blade torsion, these work out to be 46° and 31° of blade rotation respectively. Again from Ref 3.1, if the input forcing function is a symmetrical triangular waveshape, the corresponding blade rotations are 34° and 22°.

If damping is taken into account, at least for small values, the conclusion will not change drastically, i.e. as long as the input duration is longer than about 45° of rotation, the error associated with blade dynamics is not expected to be greater than 20%. This is, however, contingent upon a half sine or triangular forcing function being a good model.

From data given in the 1983 program Final Report, 50% of the observed ice impacts had a response longer than 35° of rotation and 35% had a response longer than 45° of rotation. Thus, there is evidence that a quasi-static approach would be able to interpret most of the anticipated new data. Since the evidence is not very strong in favour of the static approach, it would be necessary to collect dynamic calibration data from the propeller blade. Then, if at a later date, a dynamic blade analysis was attempted, some full scale calibration data would be available to check any dynamic model.

## 3.2 Static Calibration Of The Propeller Blade

The static calibration of the instrumented propeller blade was performed during May 1984, on the John Wurmlinger which is a floating maintenance complex, operated by Purvis Navcon Ltd. The John Wurmlinger was moved adjacent to the Canmar Careen floating drydock, where the MV Robert LeMeur was situated. The Canmar personnel on site for the calibration were: Merv Edgecombe, Ken Kirby, and Paul Spencer. Clark Norris of the Arctic Ship Safety Branch, Coast Guard Northern, also participated in these tests. Figure 3.2.1 shows the MV Robert LeMeur in drydock on the Canmar Careen.

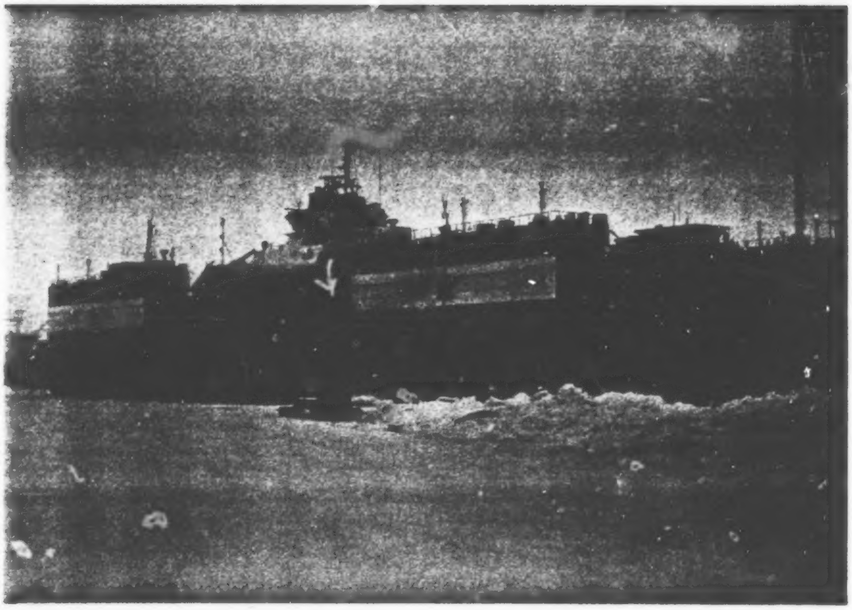
The blade calibrations were carried out on the open deck of John Wurmlinger, just to the right of the photograph. The ambient conditions, during the tests ranged from sunny to snow storms with ambient temperatures of -10°C to +5°C.

All six blade strain gauge signals together with the sliding block and load cell signal were recorded simultaneously during the static and dynamic calibrations on the John Wurmlinger. The calibration of the sliding block is discussed in Section 4.

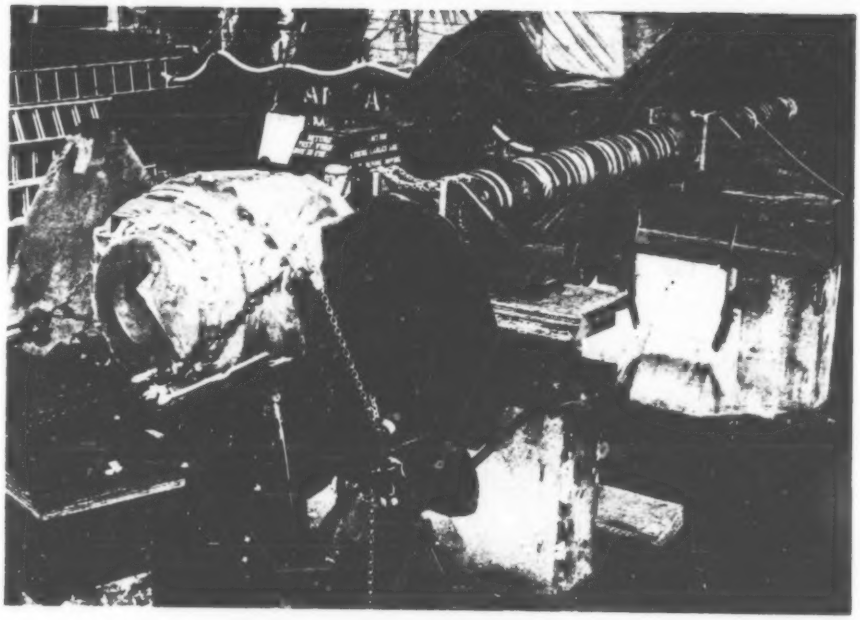
### 3.2.1 Details of Static Tests

The starboard shaft line was supported on concrete blocks and chained down by block and tackles to prevent the shaft from moving and/or rotating. This arrangement is shown in Figure 3.2.2. Loads of up to six tonnes were applied at 36 locations on the face of the blade, together with loads on the trailing edge in the plane of the blade, and loads on the tip radially towards the centre of the hub.

Up to five load orientations were applied at each location on the blade face. These first five load



| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE:<br>CANMAR CAREEN WITH M.V. ROBERT LEMEUR ON DRYDOCK<br>FIGURE No. 3.2.1 |



(ONE PROPELLER BLADE IS REMOVED)

| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE:<br>STARBOARD PROPELLER SHAFT AND HUB FROM THE M.V. ROBERT LEMEUR<br>FIGURE No. |
|---|---|---|

orientation cases were all within sixteen degrees of perpendicular to the blade face. In addition, the blade was loaded at two of its edges: The tip of the blade was loaded at Point 37, Case 6, and; The trailing edge of the blade was loaded at Point 38, Case 7. At Point 37 the loading direction was approximately radially inward, while at Point 38 the loading direction was in the plane of the blade and approximately tangential to the blade. The orientation and magnitude of the applied load, together with the response of the blade-mounted and sliding block-mounted strain gauges, were recorded for each calibration.

The hydraulic jack and load cell used to apply the load, is shown in Figure 3.2.3. The aluminum discs, which can be seen in the photograph, serve two purposes; the first is to accurately locate the point of load application, and the second is to prevent damage to the surface of the propeller blade by the load head.

In order to know the actual load applied, the load cell had been calibrated at Hoogensen Metallurgical Engineering Ltd., during May 1984. The output of the load cell was checked for loads of up to fifty kilonewtons and found to be linear, with an output of 7.318 kN/V. The maximum capacity of the load cell was ninety kilonewtons.

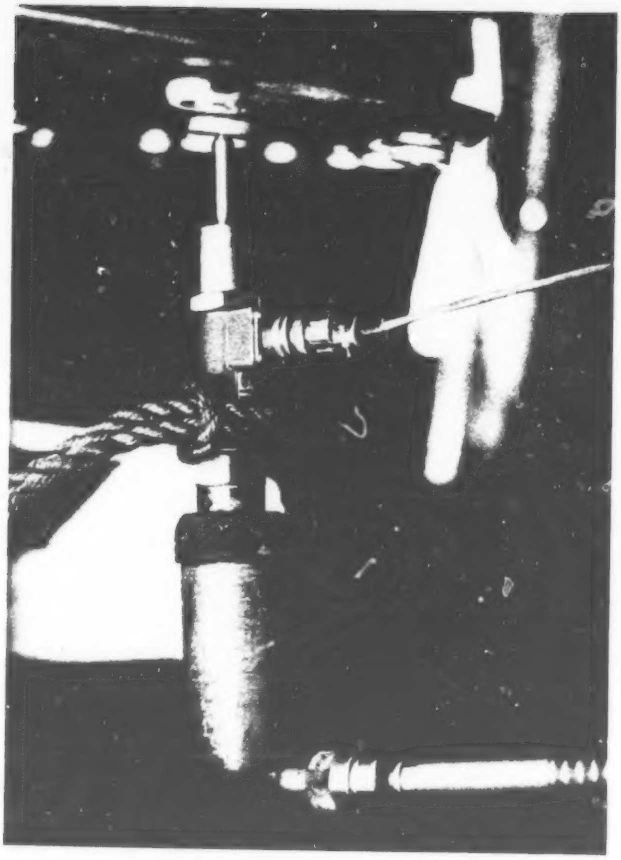
The positions of the loading points are presented in Table 3.2.1. The angle at which the load was applied, relative to the plane through the gauge locations at 0.47 relative radius, is shown in Table 3.2.2.

The loading angles for the first five load cases were obtained through the use of wedges as shown in Figure 3.2.4.

The data for the blade static calibration was collected using two different methods. During the initial setup of the calibration jig, the output of the strain gauge amplifiers (Vishay Model 2100) was read using a 4-1/2 digit multimeter. This was done because the HP6940B Multi-programmer was defective and a replacement had not arrived in time for the initial calibration tests.

During the manual calibration procedures, three to five sets of readings were taken at different load levels for each point-case combination measured.

After the replacement HP6940B arrived, data was collected using the HP9836 computer and the HP6940B voltage scanner. A copy of the computer program "HSDAR" is given in Appendix E.



CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE:
HYDRAULIC JACK AND LOAD CELL

FIGURE No. 3.2.3

CALIBRATION POINT LOCATIONS ON THE AFT SIDE
OF THE INSTRUMENTED PROPELLER BLADE

| POINT NUMBER | RELATIVE RADIUS | RELATIVE CHORD |
|---|---|---|
| 1 | .980 | .050 |
| 2 | .980 | .150 |
| 3 | .980 | .250 |
| 4 | .980 | .350 |
| 5 | .980 | .500 |
| 6 | .980 | .750 |
| 7 | .980 | .950 |
| 8 | .900 | .050 |
| 9 | .900 | .150 |
| 10 | .900 | .250 |
| 11 | .900 | .350 |
| 12 | .900 | .500 |
| 13 | .900 | .750 |
| 14 | .900 | .950 |
| 15 | .800 | .050 |
| 16 | .800 | .150 |
| 17 | .800 | .250 |
| 18 | .800 | .350 |
| 19 | .800 | .500 |
| 20 | .800 | .750 |
| 21 | .800 | .950 |
| 22 | .700 | .050 |
| 23 | .700 | .150 |
| 24 | .700 | .250 |
| 25 | .700 | .350 |
| 26 | .700 | .500 |
| 27 | .700 | .750 |
| 28 | .700 | .950 |
| 29 | .600 | .050 |
| 30 | .600 | .150 |
| 31 | .600 | .250 |
| 32 | .600 | .350 |
| 33 | .600 | .750 |
| 34 | .600 | .950 |
| 35 | .500 | .060 |
| 36 | .500 | .500 |
| 37 | 1.000 | .150 |
| 38 | .900 | 1.000 |

The relative chord is zero at the leading edge of the blade and one at the trailing edge of the blade. The relative radius is zero at the center of the hub and one at the tip of the blade.

TITLE: CALIBRATION POINT LOCATIONS ON THE AFT SIDE OF THE BLADE

TABLE 3·2·1

| LOAD CASE NUMBER | HORIZONTAL ANGLE | VERTICAL ANGLE |
|---|---|---|
| 1 | -4.000 | 0.000 |
| 2 | -16.000 | 0.000 |
| 3 | 8.000 | 0.000 |
| 4 | -4.000 | -12.000 |
| 5 | -4.000 | 12.000 |

The horizontal angle is the number of degrees in the horizontal plane, by which the angle of load application varries from perpendicular to the blade at 0.47 relative radius. Positive towards the leading edge.

The vertical angle is the number of degrees in the vertical plane, by which the angle of load application varries from perpendicular to the blade. Positive upwards.

TITLE: LOAD CASE ANGLES FOR THE VARIOUS LOAD CASES

TABLE 3·2·2

CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE:
USE OF WEDGES TO ACHIEVE VARIOUS LOAD ANGLES

FIGURE No. 3.2.4

In order to check the linearity of the system, the load on the blade was varied while voltage readings were taken of the outputs from the six blade signals, the sliding block signal and the load cell signal. Ten sets of readings were taken per second with up to 500 sets of readings recorded. Sometimes the glue on the aluminum discs would shear, causing the end of that particular calibration test.

The manually recorded values were used, on site, as inputs for the "Matrix test" computer program, see Appendix D. This computer program was used to generate an [A] Matrix as described in Section 3.1. The values input to the "Matrixtest" program were the blade strain gauge output signals recorded during the greatest load, for each case-point combination measured, with the zero offset subtracted.

### 3.2.2 Discussion of Results

The manually collected data points input to the "Matrixtest" program are listed in Table 3.2.3. For comparison purposes, the values in this table have all been scaled to the equivalent outputs at a load of 10 kN.

The computer recorded calibration signals used a different amplifier gain than the gain used during the manual and ship testing periods. This was done to achieve the same accuracy during the computer recorded calibrations as was obtained during the manual calibrations. The manual method used a digital voltmeter with a 1 mv resolution whereas the HP 6940B A/D converter had a 5 mv resolution. Thus, in order to achieve the same measurement accuracy in both sets of data, the computer collected data used 5 times the amplifier gain. For ease of comparison and use, all data presented is scaled to the same relative amplifier gain (400).

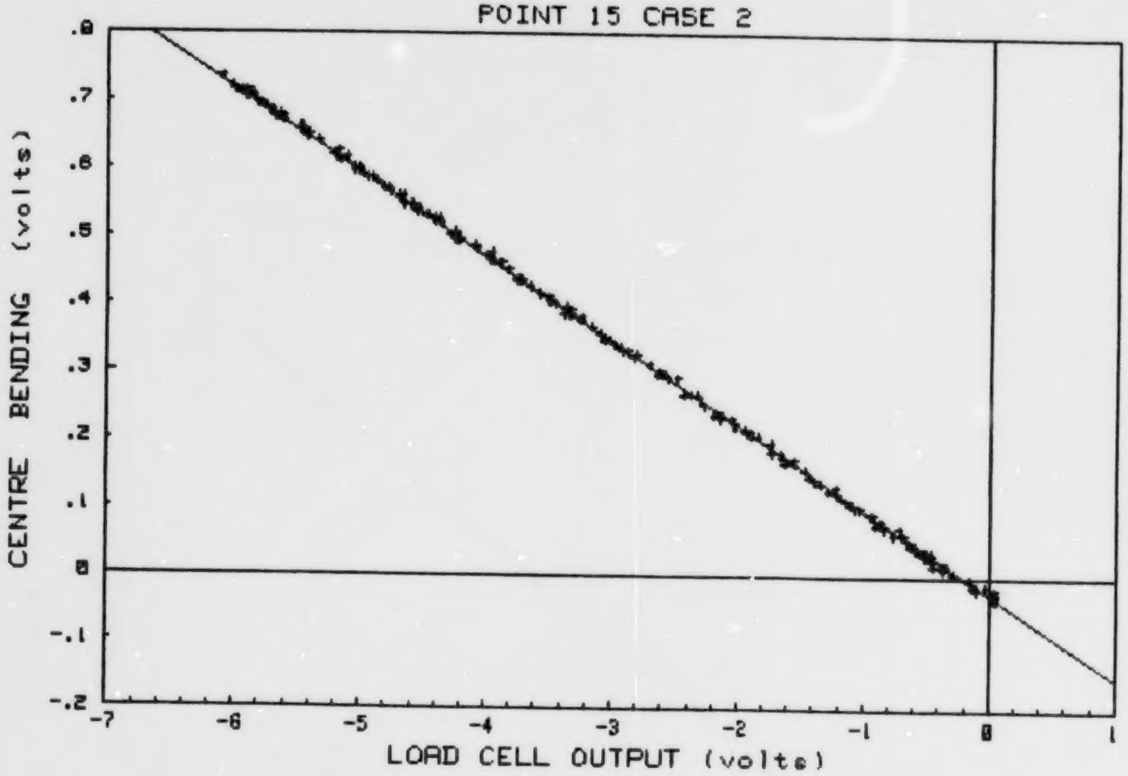
The computer recorded data obtained from a representative calibration test is plotted in Figures 3.2.5 to 3.2.10. These figures show the linear relationship between the strain gauge output signal and the load applied to the blade. The load cell output is the signal obtained from the load cell in series with the hydraulic jack. The straight line on each of these plots is the best least-squares straight line fit, for the data points. The slopes of these lines are given as the mV output per 10 kN load ratios shown in Table 3.2.4. In Table 3.2.4, the title of the data file refers to the load point and case number used during the calibration test.

DATA POINTS MANUALLY COLLECTED ON WHARMLINGER

POINTS SCALED FOR 10 kN LOADING FORCE

| POINT NUMBER | CASE NUMBER | G1 mV | G2 mV | G3 mV | G4 mV | G5 mV | G6 mV |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 179.6 | -90.5 | 237.0 | -174.6 | 70.6 | -212.1 |
| 2 | 1 | 204.9 | -88.4 | 235.5 | -175.0 | 90.3 | -170.5 |
| 3 | 1 | 222.2 | -75.4 | 227.6 | -154.4 | 107.8 | -116.8 |
| 4 | 1 | 233.2 | -59.7 | 210.0 | -116.6 | 124.3 | -66.0 |
| 5 | 1 | 247.5 | -20.1 | 184.4 | -20.8 | 150.2 | 1.3 |
| 6 | 1 | 211.3 | 69.8 | 123.4 | 109.3 | 171.3 | 63.5 |
| 7 | 1 | 175.9 | 171.2 | 82.0 | 162.2 | 188.2 | 85.6 |
| 8 | 1 | 141.4 | -80.6 | 211.7 | -146.6 | 49.0 | -226.2 |
| 9 | 1 | 159.6 | -75.8 | 210.6 | -148.0 | 69.2 | -184.4 |
| 10 | 1 | 169.[illegible] | -66.4 | 194.1 | -131.9 | 82.8 | -122.6 |
| 11 | 1 | 180.8 | -51.6 | 179.3 | -105.4 | 98.0 | -68.8 |
| 12 | 1 | 188.7 | -26.8 | 150.3 | -19.9 | 122.1 | -1.4 |
| 13 | 1 | 162.9 | 92.7 | 95.7 | 112.9 | 153.4 | 63.6 |
| 14 | 1 | 131.8 | 185.7 | 56.3 | 137.6 | 170.7 | 76.6 |
| 15 | 1 | 90.2 | -64.5 | 166.7 | -98.2 | 29.4 | -200.9 |
| 16 | 1 | 106.4 | -60.2 | 162.8 | -102.3 | 47.7 | -159.4 |
| 17 | 1 | 116.9 | -53.7 | 158.7 | -99.9 | 59.2 | -110.9 |
| 18 | 1 | 126.4 | -42.4 | 146.2 | -84.3 | 76.0 | -60.8 |
| 19 | 1 | 129.2 | -7.8 | 116.7 | -13.3 | 95.9 | .5 |
| 19 | 2 | 127.1 | -6.1 | 14.3 | -13.3 | 98.4 | 3.1 |
| 19 | 3 | 127.6 | -6.5 | 112.8 | 21.6 | 91.1 | -4.6 |
| 20 | 1 | 115.9 | 91.7 | 71.6 | 96.1 | 127.3 | 54.0 |
| 21 | 1 | 91.1 | 176.9 | 34.5 | 100.8 | 144.5 | 62.0 |
| 22 | 1 | 55.6 | -44.1 | 123.5 | -58.3 | 18.1 | -150.7 |
| 23 | 1 | 66.0 | -45.0 | 125.1 | -65.5 | 32.1 | -136.8 |
| 24 | 1 | 71.2 | -146.0 | 117.5 | -69.6 | 43.4 | -97.8 |
| 25 | 1 | 71.3 | -31.3 | 106.9 | -57.6 | 54.1 | -56.0 |
| 26 | 1 | 71.9 | -5.3 | 87.8 | 14.8 | 72.7 | 0.0 |
| 27 | 1 | 66.6 | 79.8 | 48.4 | 64.2 | 97.5 | 40.3 |
| 28 | 1 | 56.8 | 147.4 | 18.9 | 60.5 | 112.5 | 45.6 |
| 29 | 1 | 26.3 | -26.1 | 77.2 | -23.8 | 8.4 | -97.1 |
| 30 | 1 | 31.4 | -27.3 | 76.4 | -28.9 | 16.9 | -90.6 |
| 31 | 1 | 31.7 | -25.6 | 72.2 | -27.8 | 24.8 | -73.3 |
| 32 | 1 | 28.1 | -17.2 | 62.8 | -17.0 | 32.7 | -31.9 |
| 33 | 1 | 25.7 | 66.3 | 27.6 | 24.9 | 64.1 | 28.7 |
| 34 | 1 | 30.3 | 100.0 | 10.1 | 24.5 | 78.9 | 28.4 |
| 35 | 1 | 7.0 | -15.6 | 32.4 | -7.4 | 2.3 | -28.1 |
| 36 | 1 | -9.6 | -8.5 | 16.1 | 1.1 | -1.4 | 5.2 |
| 37 | 6 | -21.4 | 3.6 | -22.1 | 14.3 | -11.4 | 12.1 |
| 38 | 7 | -13.0 | 10.6 | -16.3 | -9.3 | -26.9 | -8.8 |

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: MANUALLY OBTAINED STRAIN GAUGE OUTPUTS<br>TABLE 3·2·3 |

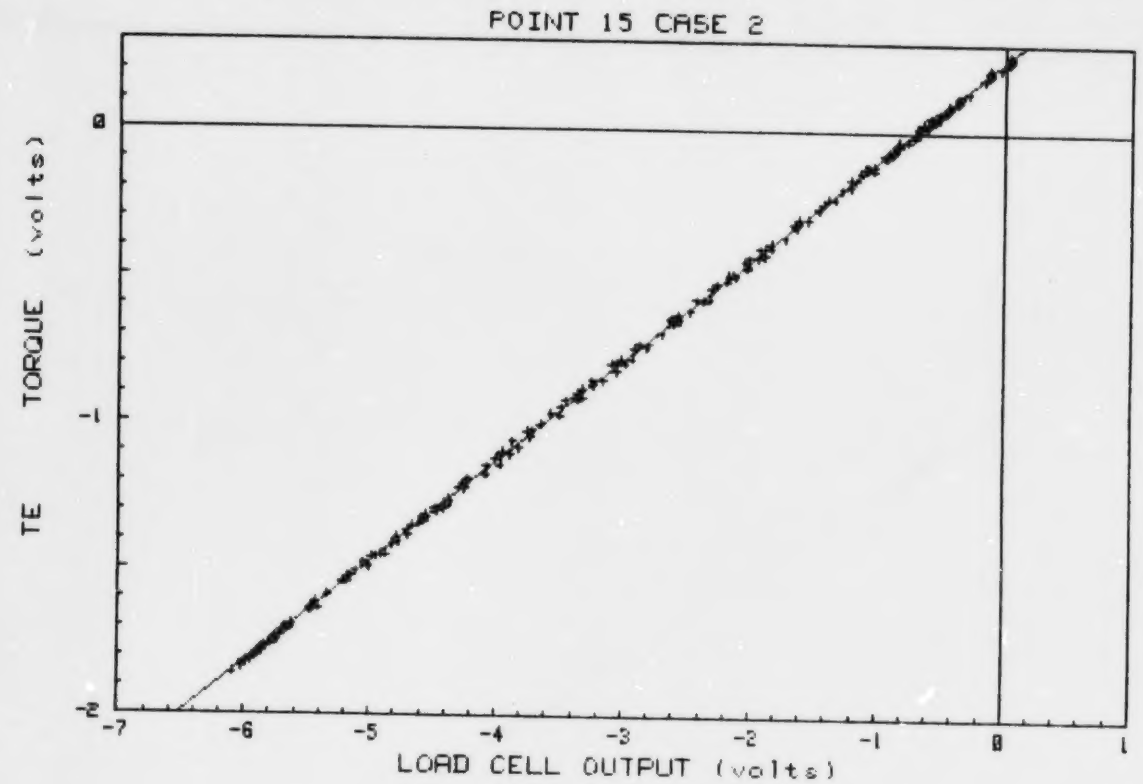


**CANADIAN MARINE DRILLING LIMITED**

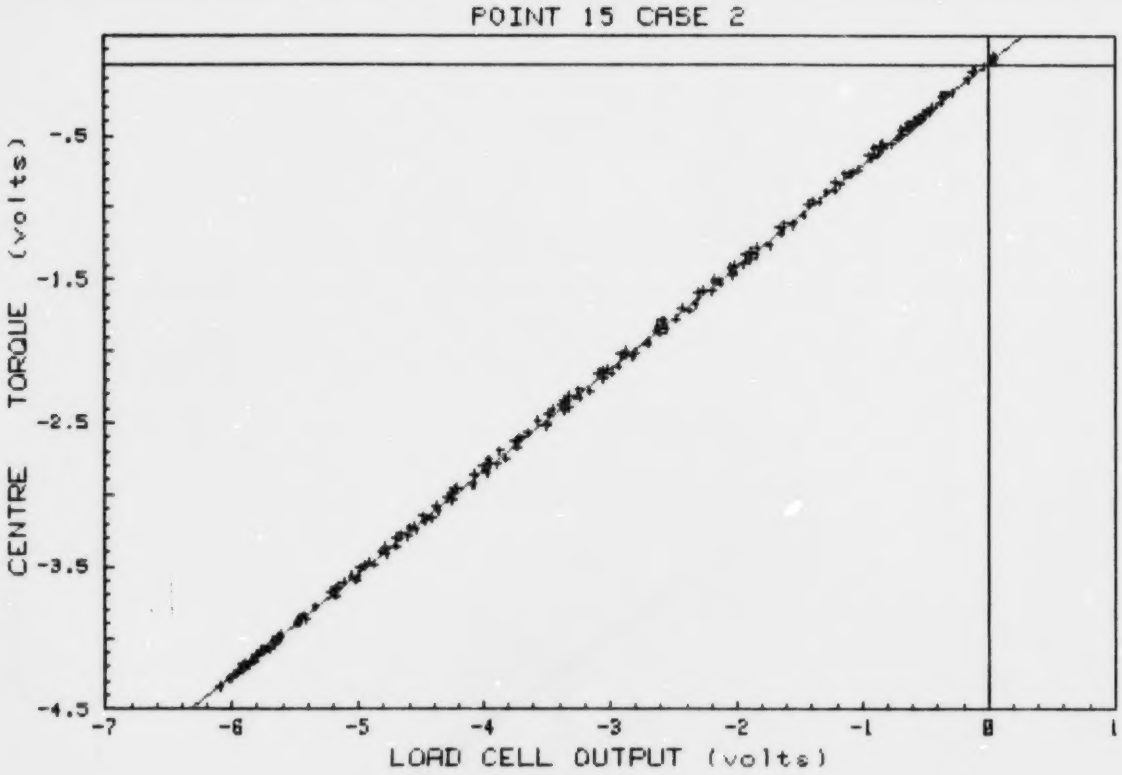
**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** STATIC CALIBRATION, WURMLINGER CENTRE BENDING VS LOAD CELL OUTPUTS PT15-C2

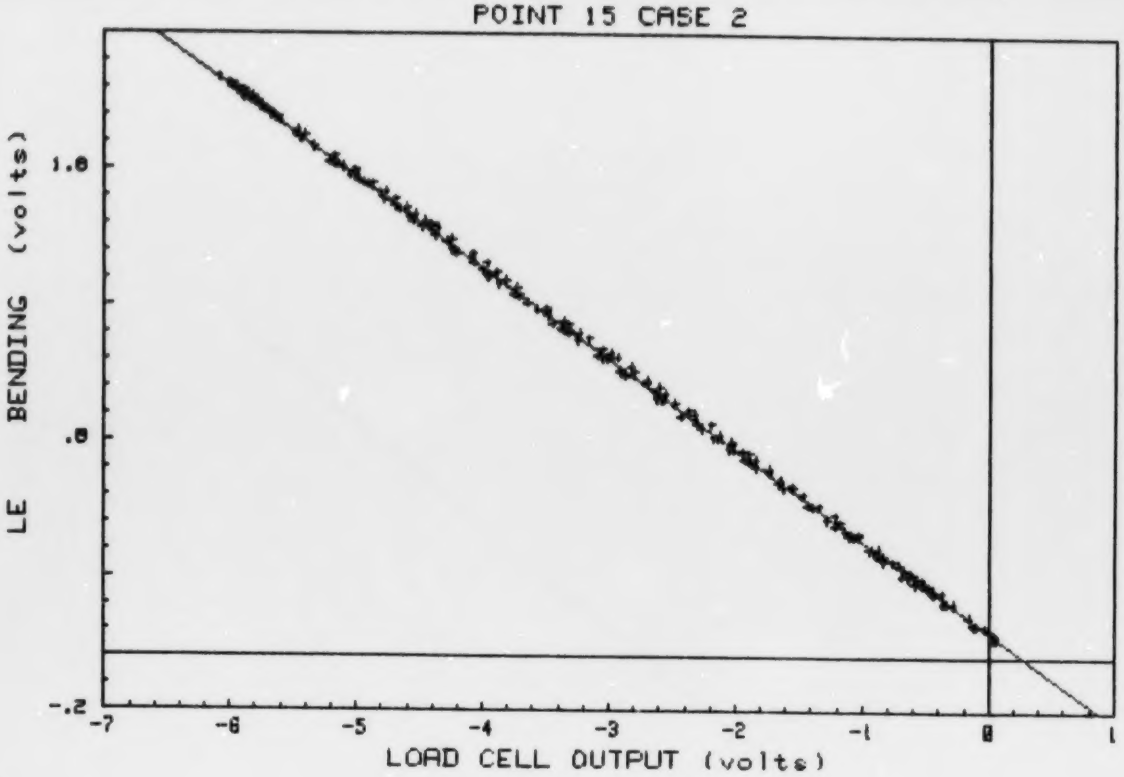
**FIGURE No. 3.2.5**



| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE: STATIC CALIBRATION, WURMLINGER<br>T.E. TORQUE VS LOAD CELL OUTPUTS<br>PT15-C2 |
| | | FIGURE No. 3.2.6 |



| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | **TITLE: STATIC CALIBRATION, WURMLINGER CENTRE TORQUE VS LOAD CELL OUTPUTS PT15-C2** |
| | | **FIGURE No. 3.2.7** |



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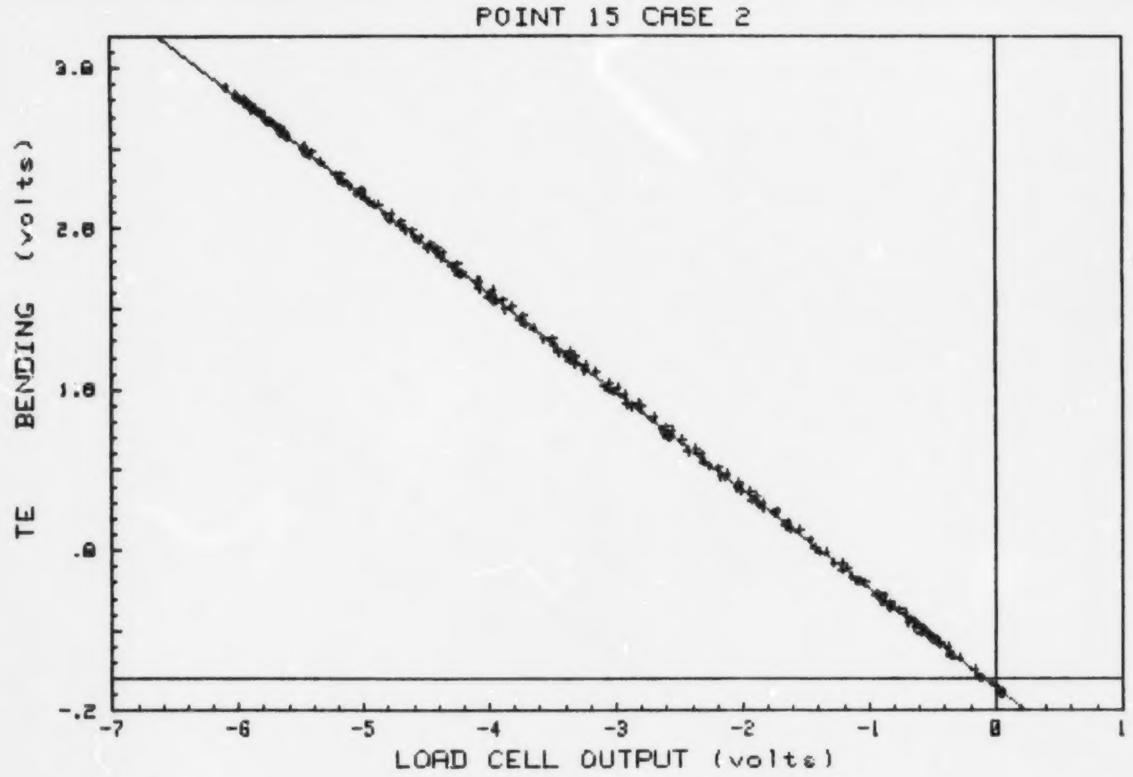
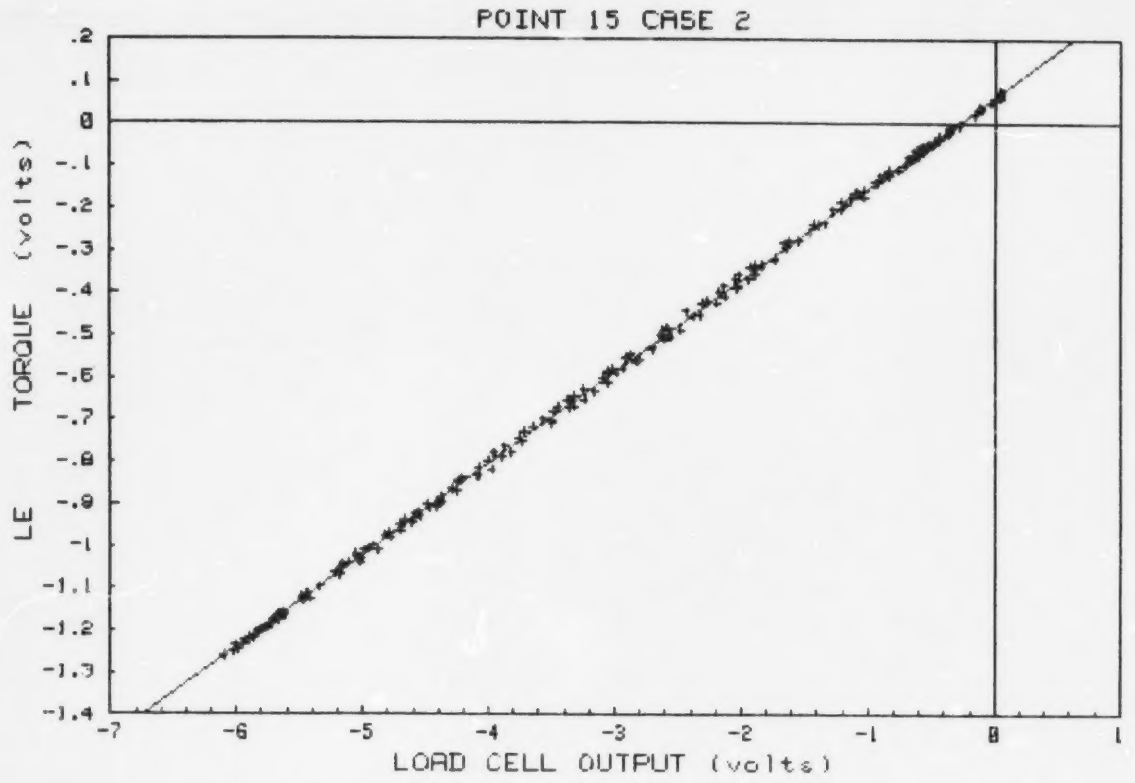
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE: STATIC CALIBRATION, WURMLINGER<br>L.E. BENDING VS LOAD CELL OUTPUTS<br>PT15-C2 |
| | | FIGURE No. 3.2.8 |



| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | **TITLE: STATIC CALIBRATION, WURMLINGER T.E. BENDING VS LOAD CELL OUTPUTS PT15-C2** |
| | | **FIGURE No. 3.2.9** |



| | | |
|---|---|---|
| **CANADIAN<br>MARINE<br>DRILLING<br>LIMITED** | **MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS** | **TITLE: STATIC CALIBRATION, WURMLINGER<br>L.E. TORQUE VS LOAD CELL OUTPUTS<br>PT15-C2** |
| | | **FIGURE No. 3.2.10** |

AMPLIFIER GAINS USED ARE: CH1-6 400; CH7 1000; CH8 500

GAGE OUTPUT VOLTAGE PER APPLIED LOAD ( mV/10kN )

| TITLE | GAGE #1 | GAGE #2 | GAGE #3 | GAGE #4 | GAGE #5 | GAGE #6 | GAGE #7 |
|---|---|---|---|---|---|---|---|
| PT1_C2 | 199.104 | -97.174 | 262.317 | -189.741 | 82.747 | -230.132 | -107.200 |
| PT1_C3 | 190.416 | -100.001 | 249.815 | -191.484 | 68.996 | -236.194 | -70.109 |
| PT2_C1 | 216.622 | -94.782 | 251.686 | -187.309 | 92.994 | -185.202 | -71.393 |
| PT2_C1_2 | 212.290 | -93.923 | 246.746 | -185.855 | 89.142 | -184.613 | -58.141 |
| PT2_C2 | 216.697 | -88.161 | 252.132 | -178.559 | 101.046 | -170.954 | -70.089 |
| PT2_C3 | 211.985 | -94.042 | 245.028 | -184.638 | 88.357 | -182.291 | -57.757 |
| PT4_C2 | 233.508 | -58.445 | 216.487 | -115.580 | 130.476 | -60.573 | -51.488 |
| PT4_C3 | 230.156 | -64.759 | 209.597 | -121.245 | 119.340 | -69.049 | 2.095 |
| PT4_C5 | 235.734 | -61.426 | 217.038 | -118.905 | 127.818 | -63.172 | -45.265 |
| PT5_C3 | 234.660 | -23.604 | 174.987 | -25.290 | 140.136 | 4.667 | 5.950 |
| PT5_C5 | 239.634 | -21.952 | 182.470 | -27.391 | 146.530 | 5.932 | -15.577 |
| PT7_C2 | 187.593 | 177.082 | 93.251 | 168.838 | 204.074 | 92.816 | 299.606 |
| PT7_C3 | 185.922 | 183.930 | 84.799 | 175.739 | 199.725 | 92.986 | 346.119 |
| PT7_C4 | 188.504 | 184.106 | 89.964 | 174.517 | 207.108 | 94.229 | 293.633 |
| PT8_C3 | 145.763 | -86.241 | 219.013 | -154.595 | 47.677 | -239.191 | -84.622 |
| PT9_C2 | 166.049 | -77.550 | 220.544 | -148.312 | 76.913 | -180.512 | -79.631 |
| PT9_C3 | 164.712 | -82.807 | 215.779 | -155.582 | 67.903 | -191.323 | -87.017 |
| PT9_C3_2 | 212.534 | -94.421 | 245.854 | -185.560 | 89.760 | -183.070 | -54.946 |
| PT10_C2 | 173.625 | -64.812 | 203.290 | -131.107 | 92.393 | -119.844 | -78.783 |
| PT10_C3 | 176.040 | -73.588 | 203.046 | -142.039 | 83.048 | -136.431 | -45.232 |
| PT10_C4 | 172.250 | -68.718 | 200.893 | -135.436 | 86.477 | -127.362 | -30.358 |
| PT11_C2 | 186.393 | -50.629 | 189.375 | -103.850 | 108.965 | -66.697 | -53.568 |
| PT11_C4 | 184.250 | -53.413 | 184.967 | -105.330 | 103.777 | -70.408 | -34.254 |
| PT12_C2 | 200.704 | -13.245 | 163.932 | -21.014 | 136.850 | 3.794 | -6.375 |
| PT12_C2_2 | 202.224 | -13.613 | 164.723 | -21.337 | 137.249 | 3.522 | -2.234 |
| PT12_C3 | 197.478 | -17.144 | 156.285 | -23.099 | 124.967 | -1.675 | 5.354 |
| PT15_C2 | 98.170 | -63.704 | 179.119 | -100.505 | 36.401 | -208.564 | -119.176 |
| PT15_C3 | 97.682 | -65.812 | 174.878 | -104.736 | 29.486 | -214.612 | -80.968 |
| PT17_C2 | 127.270 | -54.588 | 170.909 | -103.432 | 71.490 | -118.306 | -53.325 |
| PT17_C3 | 123.907 | -57.567 | 163.303 | -106.736 | 60.001 | -127.612 | -28.442 |
| PT19_C3 | 130.907 | -9.647 | 117.561 | -18.834 | 95.391 | -2.723 | 6.248 |
| PT20_C3 | 123.599 | 85.905 | 75.862 | 95.667 | 128.770 | 51.554 | 86.493 |
| PT21_C2 | 104.392 | 183.584 | 44.222 | 111.728 | 159.358 | 69.316 | 350.387 |
| PT22_C2 | 59.111 | -44.975 | 130.584 | -58.907 | 21.666 | -162.003 | -77.891 |
| PT22_C3 | 61.103 | -47.309 | 130.890 | -63.392 | 18.103 | -169.880 | -102.340 |
| PT24_C2 | 73.355 | -39.745 | 123.401 | -64.523 | 48.326 | -97.156 | -63.067 |
| PT24_C3 | 73.784 | -41.937 | 121.434 | -68.065 | 43.320 | -104.762 | -18.016 |
| PT24_C4 | 74.127 | -42.309 | 122.692 | -67.655 | 45.008 | -103.913 | -51.525 |
| PT24_C5 | 75.396 | -40.740 | 124.986 | -66.904 | 48.281 | -99.557 | -28.529 |
| PT25_C2 | 74.583 | -31.165 | 113.296 | -59.002 | 60.341 | -54.572 | -35.115 |
| PT25_C3 | 75.932 | -34.201 | 112.575 | -63.001 | 56.046 | -61.214 | -4.139 |
| PT29_C2 | 29.895 | -28.456 | 83.684 | -28.188 | 10.731 | -103.232 | -39.275 |
| PT29_C3 | 28.458 | -28.360 | 82.018 | -27.851 | 6.518 | -106.542 | -41.335 |
| PT30_C2 | 31.477 | -27.318 | 78.679 | -28.975 | 18.280 | -92.397 | -44.876 |
| PT31_C2 | 31.931 | -25.779 | 74.866 | -28.335 | 27.305 | -73.653 | -48.595 |
| PT32_C2 | 24.850 | -22.325 | 69.676 | -22.829 | 36.167 | -37.577 | -26.279 |
| PT32_C3 | 27.200 | -23.140 | 70.230 | -25.502 | 34.090 | -43.064 | 1.369 |
| PT33_C3 | 27.144 | 65.296 | 30.129 | 26.167 | 68.630 | 28.593 | 69.326 |
| PT34_C2 | 33.124 | 110.630 | 10.576 | 27.353 | 88.566 | 32.435 | 253.620 |
| PT35_C2 | 9.411 | -12.015 | 38.012 | -7.749 | 3.081 | -30.050 | -33.243 |

CANADIAN
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MEASUREMENT OF ICE
PROPELLER INTERACTION
PARAMETERS

TITLE: STRAIN GAUGE OUTPUTS
USING COMPUTER DATA
ACQUISITIONS, WURMLINGER
TESTS

TABLE : 3.2.4

In the calibration test shown in Figure 3.2.5 (PT15-C2), the applied force was increased to a maximum, decreased to near zero, increased to near the same maximum and then returned to zero. This was done to test for hysteresis in the signal.

There was no significant hysteresis in the signals from the blade strain gauges.

Three of the load case - load point combinations were repeated to check the repeatability of the testing procedure. To do this, the load cell and hydraulic jack were removed and then repositioned for the same point and load case. Of the three repeat tests, all show good similarity.

The manually collected data was compiled and analyzed by the "Matrixtest" program (Appendix D) in order to verify that the set of blade strain gauges was behaving as expected. The details of the procedure are described in Section 3.1. Data is presented in Figures 3.2.11 to 3.2.16 and is in general accord with expectation. The data in Figure 3.2.16 represents the case when the blade was loaded essentially in the blade plane. This data point verifies that we cannot measure in-plane bending moment with acceptable accuracy. Other data points are only marginally in the blade plane.

## 3.3 Dynamic Calibration Tests

The purpose of the dynamic calibrations was to record dynamic blade response in case it was required for subsequent dynamic analysis of the blade response. The dynamic calibrations were also used to measure the natural frequencies of the blade in air.

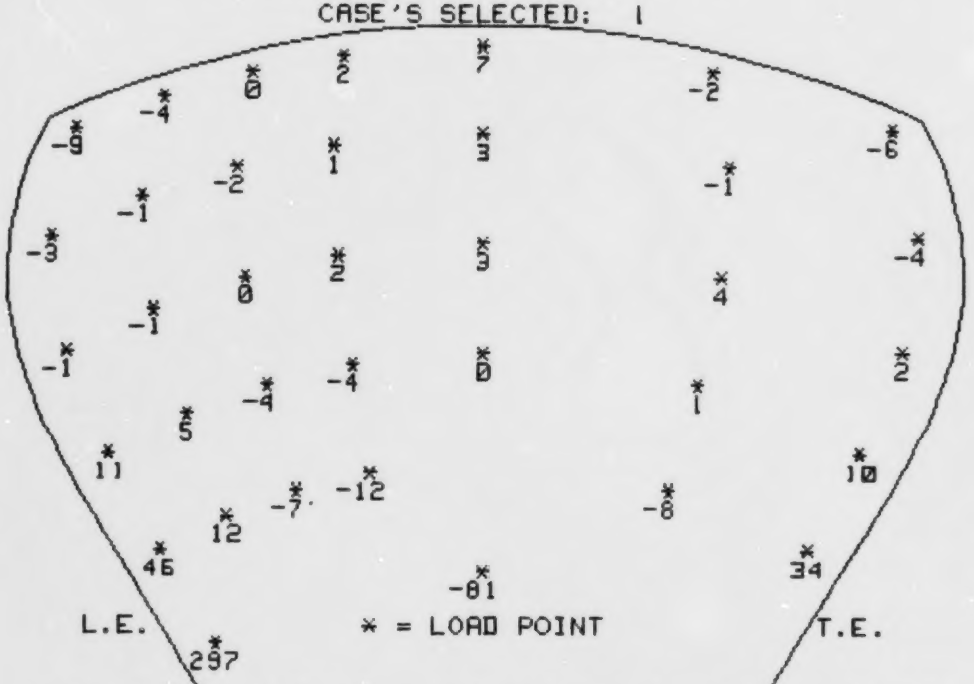
The dynamic calibrations of the propeller blade and sliding block strain gauges were performed at the same location and time as the static blade calibrations. The jig used to hold the shafting and hub in place was the same, but different methods were used to apply the load to the blade because the force exerted by the hydraulic jack could not be varied fast enough to simulate an actual ice/propeller interaction.

Twenty dynamic loading cases were recorded using two wood blocks of different mass. There were eight impacts to the forward face of the blade using a hand-held 60 kg. wood block and load cell, as shown in Figure 3.3.1, and twelve impacts to the aft side of the blade using a 200 kg. wood block suspended by chains.

ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS

8 Nov 1984 08:33:56 VERSION NO: 1.00
DATA - IN-PLANE BENDING MOMENT - % DIFFERENCE
CASE - 1
AVERAGE DIFFERENCE - 16 %

CASE'S SELECTED: 1



N.B. Based on "A" matrix generated from Case 1, manually collected data

CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE PROPELLER
INTERACTION PARAMETERS

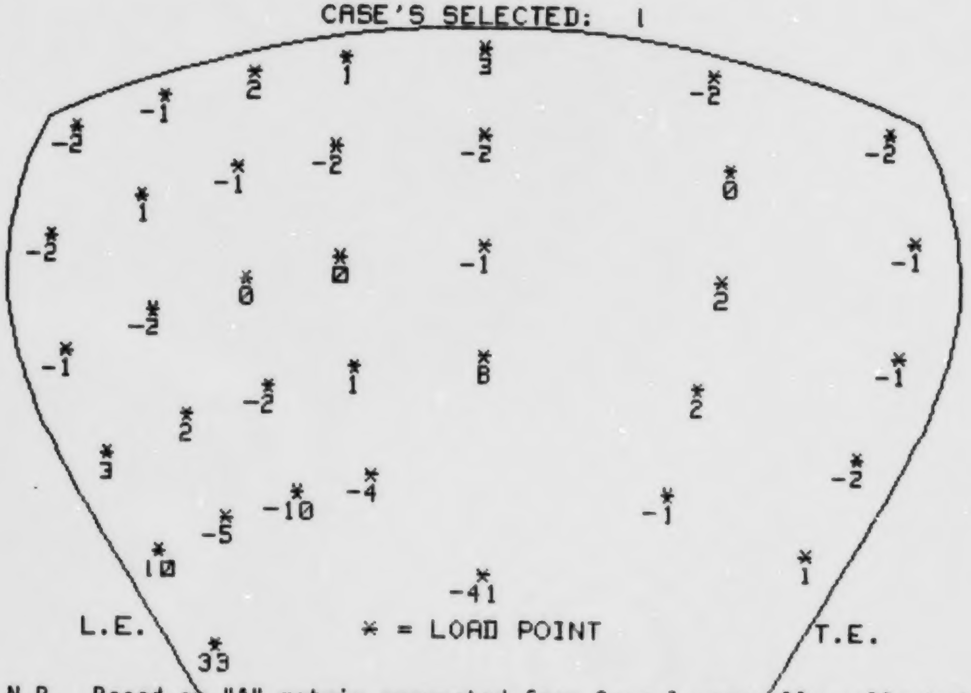
TITLE: PREDICTED VS ACTUAL IN-PLANE BENDING MOMENT, CASE ONE

FIGURE No. 3·2·11

## ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS

8 Nov 1984 08:30:53 VERSION NO: 1.00
DATA - OUT-OF-PLANE BENDING MOMENT - % DIFFERENCE
CASE - 1
AVERAGE DIFFERENCE - 4 %

CASE'S SELECTED: 1



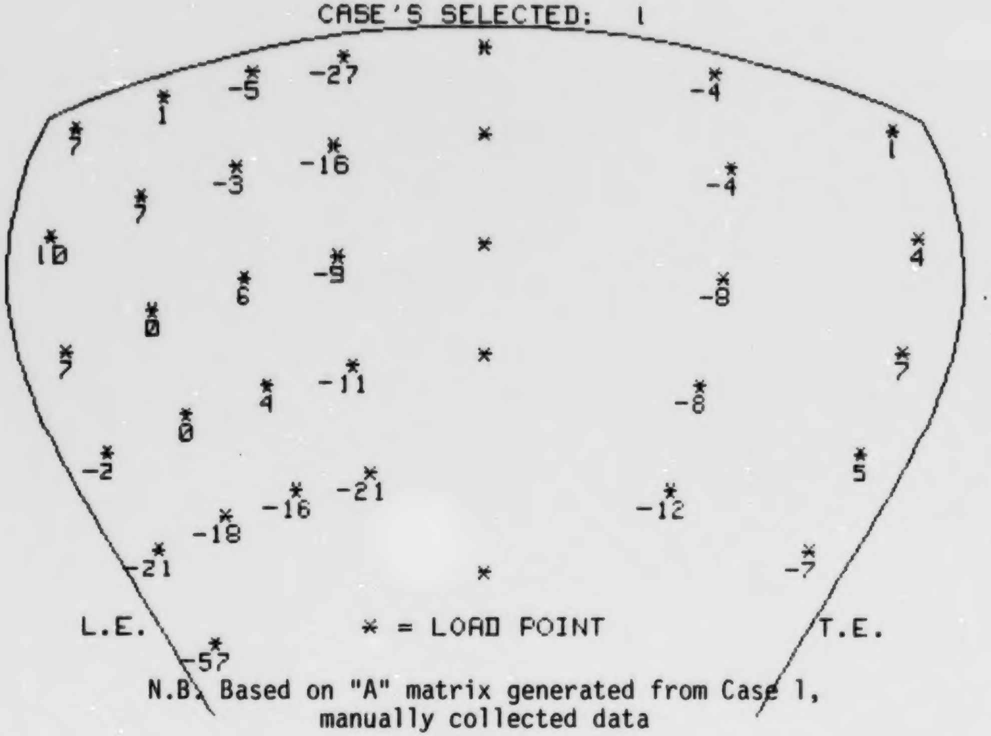
N.B. Based on "A" matrix generated from Case 1, manually collected data

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: PREDICTED VS ACTUAL OUT-OF-PLANE BENDING MOMENT, CASE ONE<br>FIGURE No. 3·2·12 |

ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS

8 Nov 1984 08:31:19 VERSION NO: 1.00
DATA - SPINDLE TORQUE - % DIFFERENCE
CASE - 1
AVERAGE DIFFERENCE - 9 %

CASE'S SELECTED: 1



N.B. Based on "A" matrix generated from Case 1,
manually collected data

CANADIAN MARINE DRILLING LIMITED

MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE: ACCURACY OF PREDICTED VS ACTUAL SPINDLE TORQUE FOR CASE ONE

FIGURE No. 3·2·13

## ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS

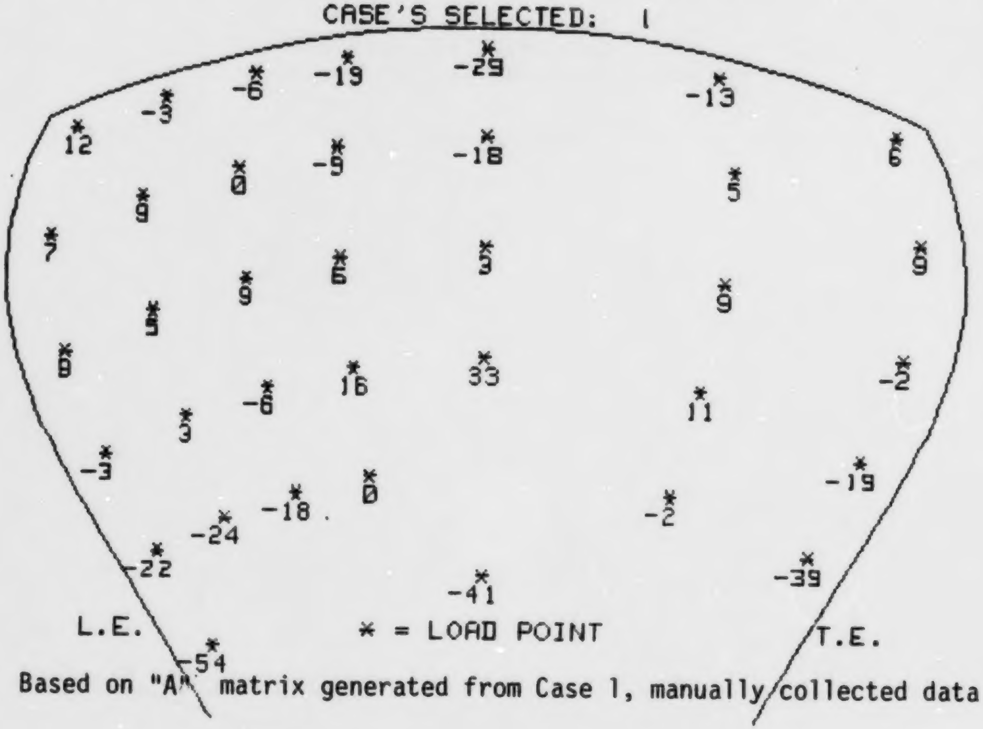
8 Nov 1984 08:30:25 VERSION NO: 1.00

DATA - OUT-OF-PLANE FORCE - % DIFFERENCE

CASE - 1

AVERAGE DIFFERENCE - 13 %

CASE'S SELECTED: 1



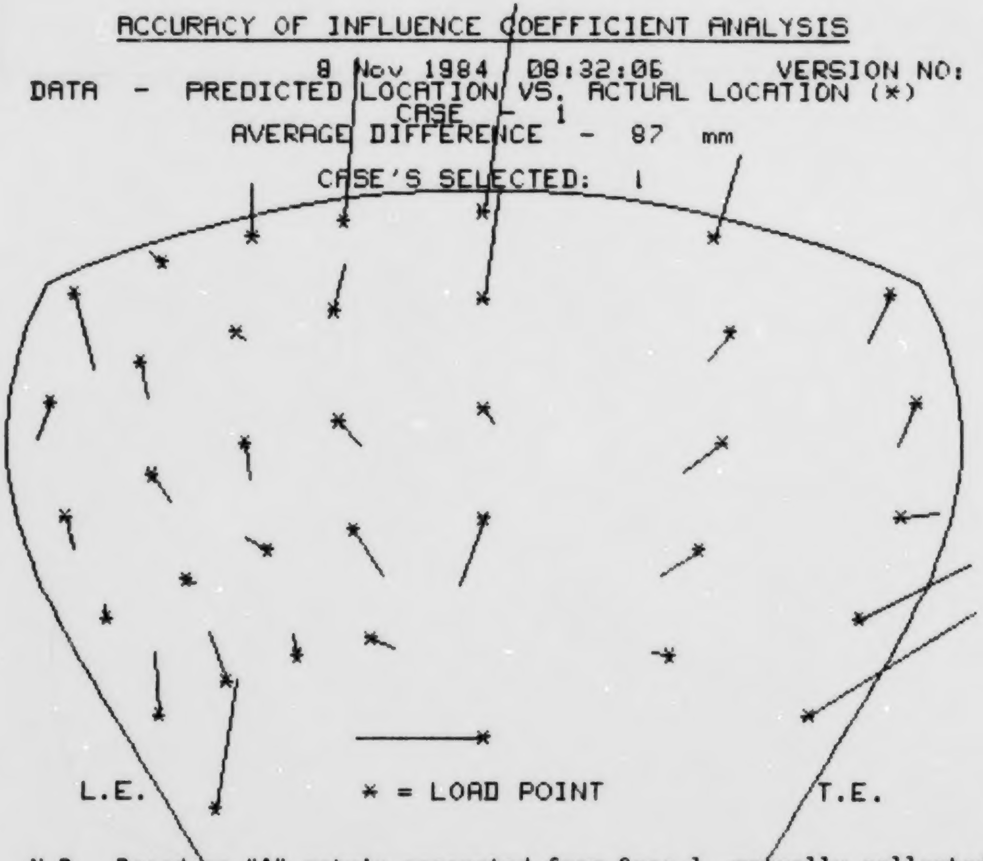
N.B. Based on "A" matrix generated from Case 1, manually collected data

| | | |
|---|---|---|
| **CANADIAN<br>MARINE<br>DRILLING<br>LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | TITLE: **ACCURACY OF PREDICTED VS ACTUAL OUT-OF-PLANE FORCE FOR CASE ONE**<br>FIGURE No. **3·2·14** |

ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS

8 Nov 1984 08:32:06 VERSION NO: 1.00
DATA - PREDICTED LOCATION VS. ACTUAL LOCATION (*)
CASE - 1
AVERAGE DIFFERENCE - 87 mm

CASE'S SELECTED: 1



N.B. Based on "A" matrix generated from Case 1, manually collected data

CANADIAN
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LIMITED

MEASUREMENT OF ICE PROPELLER
INTERACTION PARAMETERS

TITLE: PREDICTED VS ACTUAL LOAD LOCATION CASE ONE

FIGURE No. 3·2·15

ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS

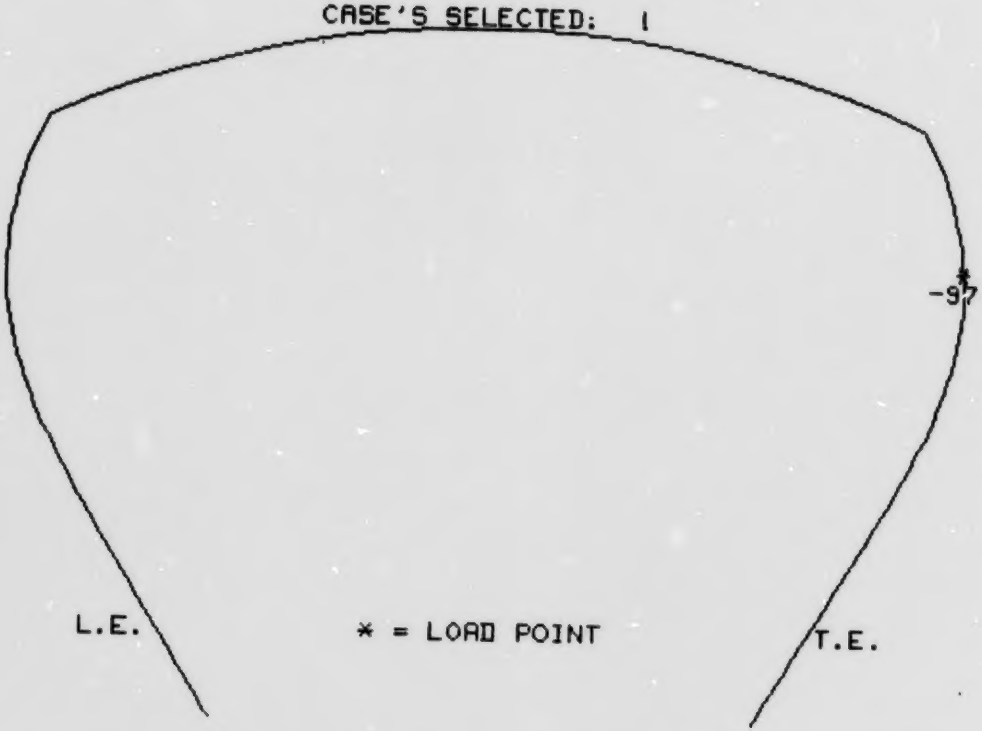
11 Nov 1984 10:06:48 VERSION NO: 1.01

DATA - IN-PLANE BENDING MOMENT - % DIFFERENCE

CASE - 7

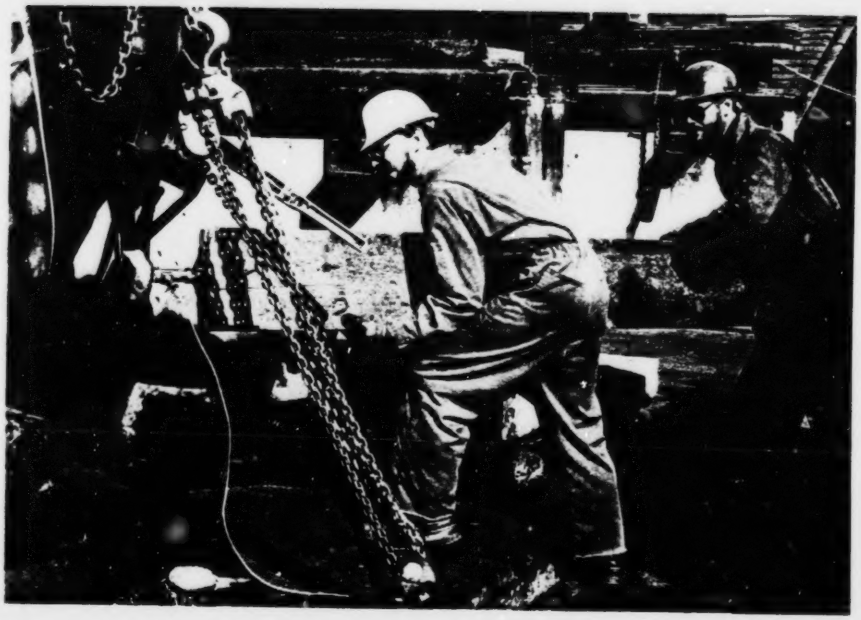
AVERAGE DIFFERENCE - 97 %

CASE'S SELECTED: 1



N.B. Based on "A" matrix generated from Case 1, manually collected data

| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | TITLE: **ACCURACY OF PREDICTED VS ACTUAL IN-PLANE BENDING MOMENT CASE 7** |
| | | FIGURE No. **3·2·16** |



| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: DYNAMIC CALIBRATION OF PROPELLER BLADE USING THE 60 KG. WOOD BLOCK |
|---|---|---|
| | | FIGURE No. 3.3.1 |

The dynamic impacts simulated various loading conditions by using two blocks of different mass, by hitting both blade faces and by using various force rise times. The different force rise times were achieved by placing substances at the block-blade interface which had different Young's Moduli and crushing strengths. The fast rise time dynamic impacts used wood at the block-blade interface, while the slow rise times used sea ice at the block-blade interface.

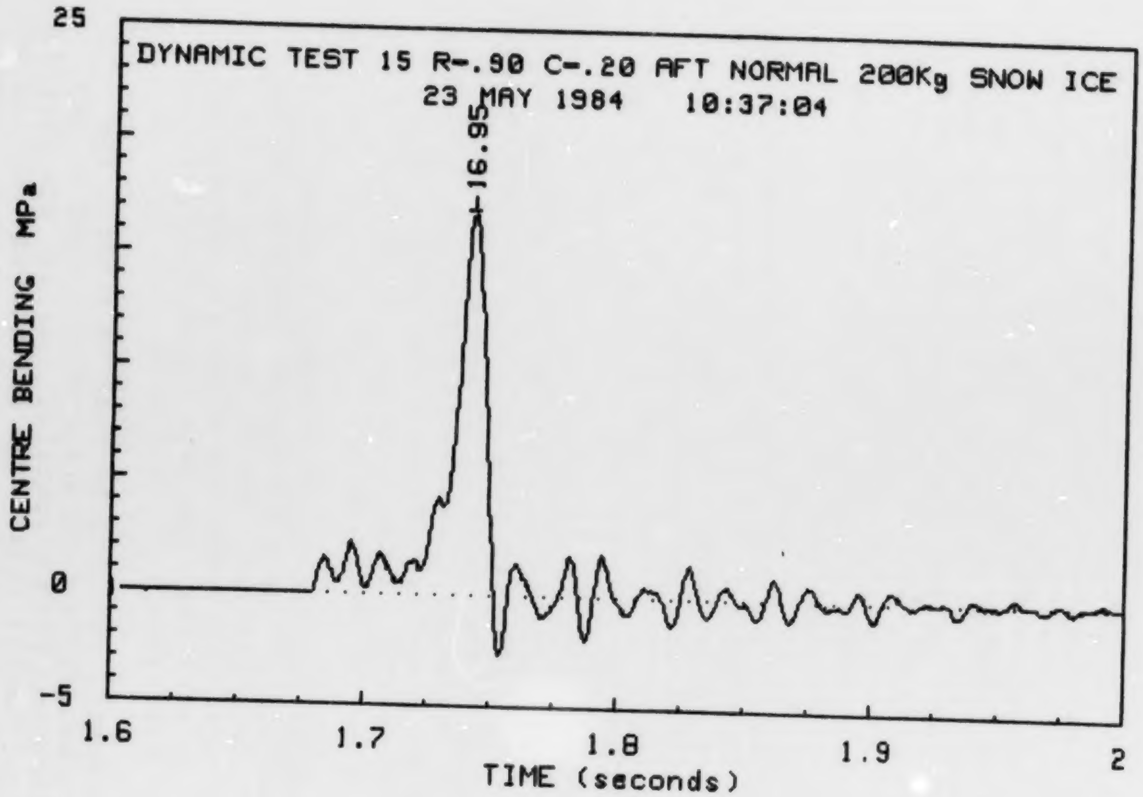
The plots of signal and calibration data presented in this section were all recorded or calculated as a result of dynamic calibration test number 15 (see Appendix F for program listing). During the dynamic tests, the computer recorded 8,000 readings for each of the 8 data channels at a scan rate of approximately 2,016 readings per channel per second. The time period presented here is the most interesting portion of the nearly 3.5 seconds of data recorded. Note that the computer was manually triggered for these tests and the 3.5 second window was long enough to allow event capture.

The response of the six blade signals to the dynamic load are shown in Figures 3.3.2 to 3.3.7. The outputs are plotted as stress versus time. The response of the sliding block signal is plotted in Figure 3.3.8. The steady state portion of the data has steps in it, due to the 5 mV resolution of the analogue to digital (A-to-D) coverter.

The force applied to the blade face is plotted in Figure 3.3.9. The first increase of the signal above the zero level is due to the crushing of the ice attached to the load cell. The sharp rise in the force occurs when the wood backing up the ice contacts the blade. An interesting observation is that the peak sliding block force occurs after the peak applied load.

The recorded data is used to generate three calculated quantities: Bending moment; Spindle torque, and Force. These quantities are calculated using the [A] Matrix and the six recorded blade signals. The predicted values are calculated for each data point recorded, and are plotted in Figures 3.3.10 to 3.3.12.

The [A] Matrix can alos be used to predict the radial and circumferential location of the load at any time and is done and circumferential loations are plotted in Figures 3.3.13 and 3.3.14. The calculated location is widely scattered even away from the blade surface. These large changes in the calculated quantity are due to noise in the signal when there is no applied load.



CANADIAN
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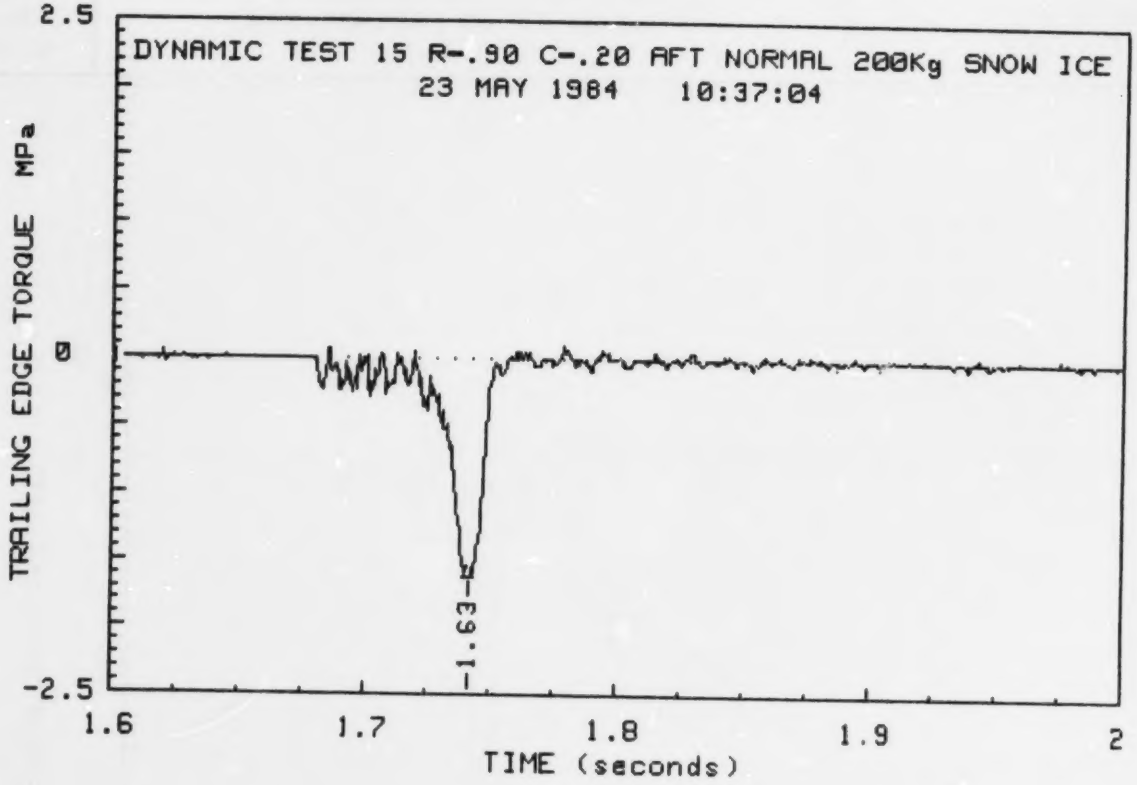
LIMITED

MEASUREMENT OF ICE PROPELLER
INTERACTION PARAMETERS

TITLE: CENTRE BENDING
DYNAMIC RESPONSE

FIGURE No. 3·3·2

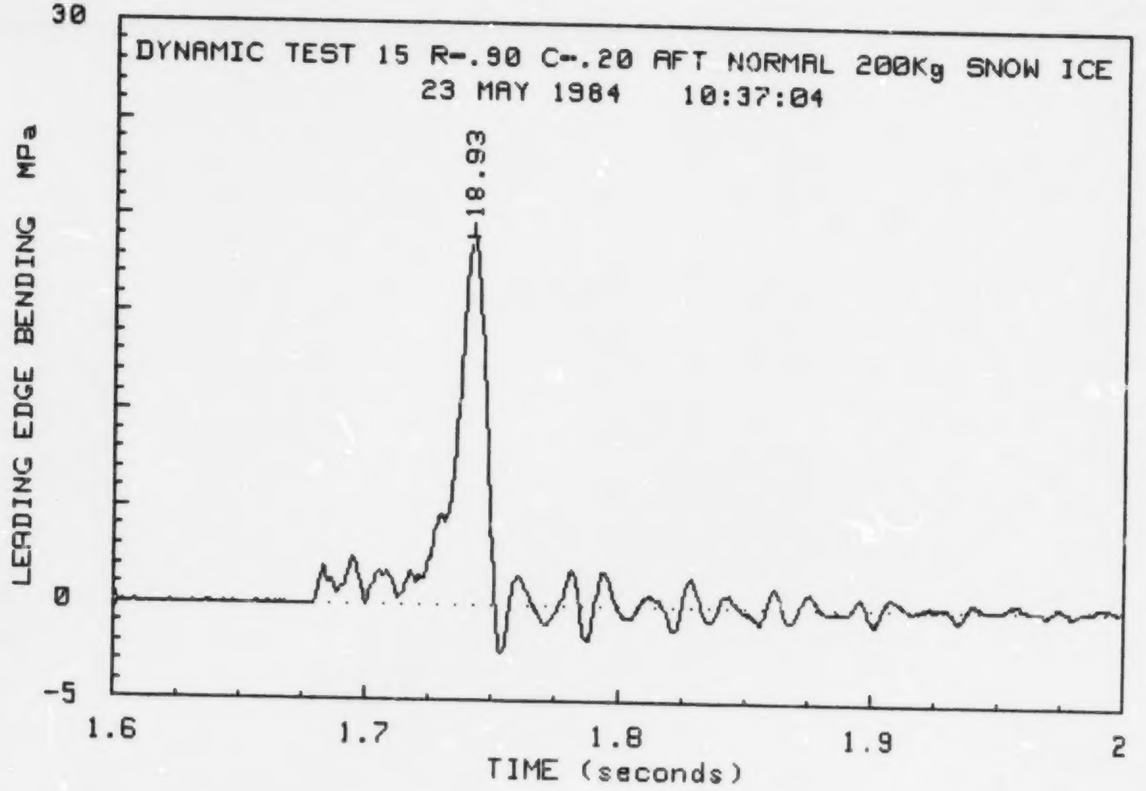


**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** TRAILING EDGE TORQUE DYNAMIC RESPONSE

**FIGURE No.** 3·3·3

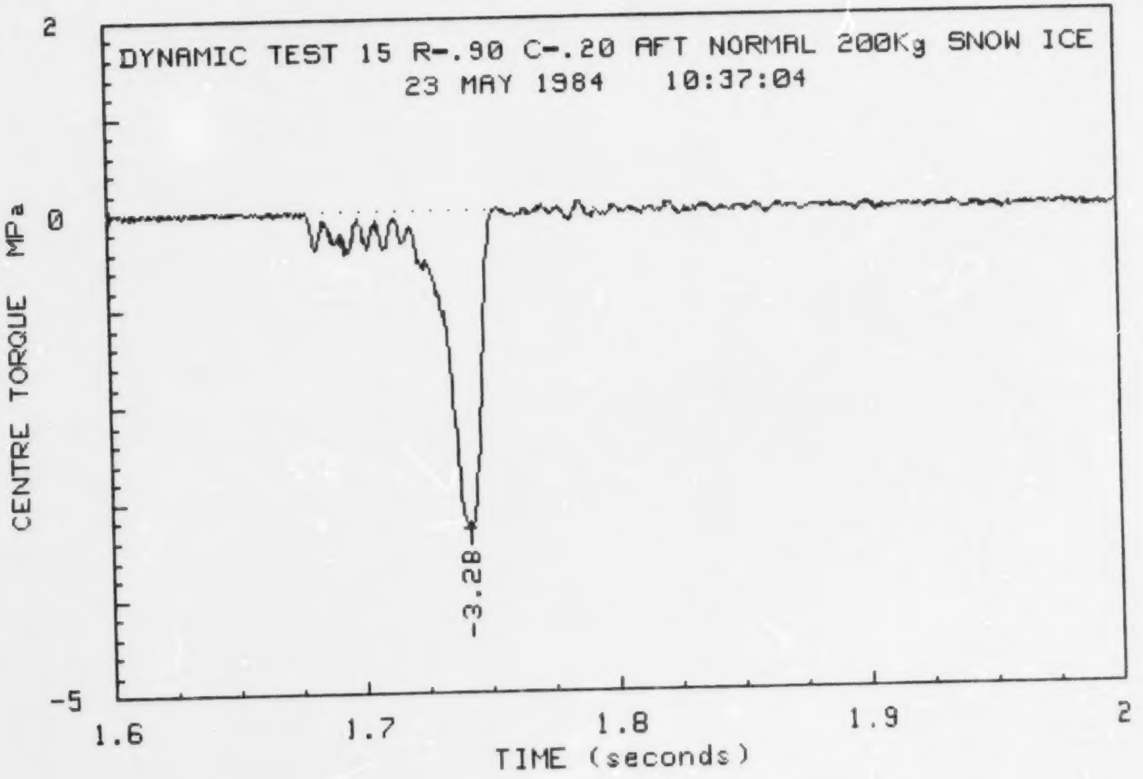


**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

TITLE: **LEADING EDGE BENDING DYNAMIC RESPONSE**

FIGURE No. 3·3·4

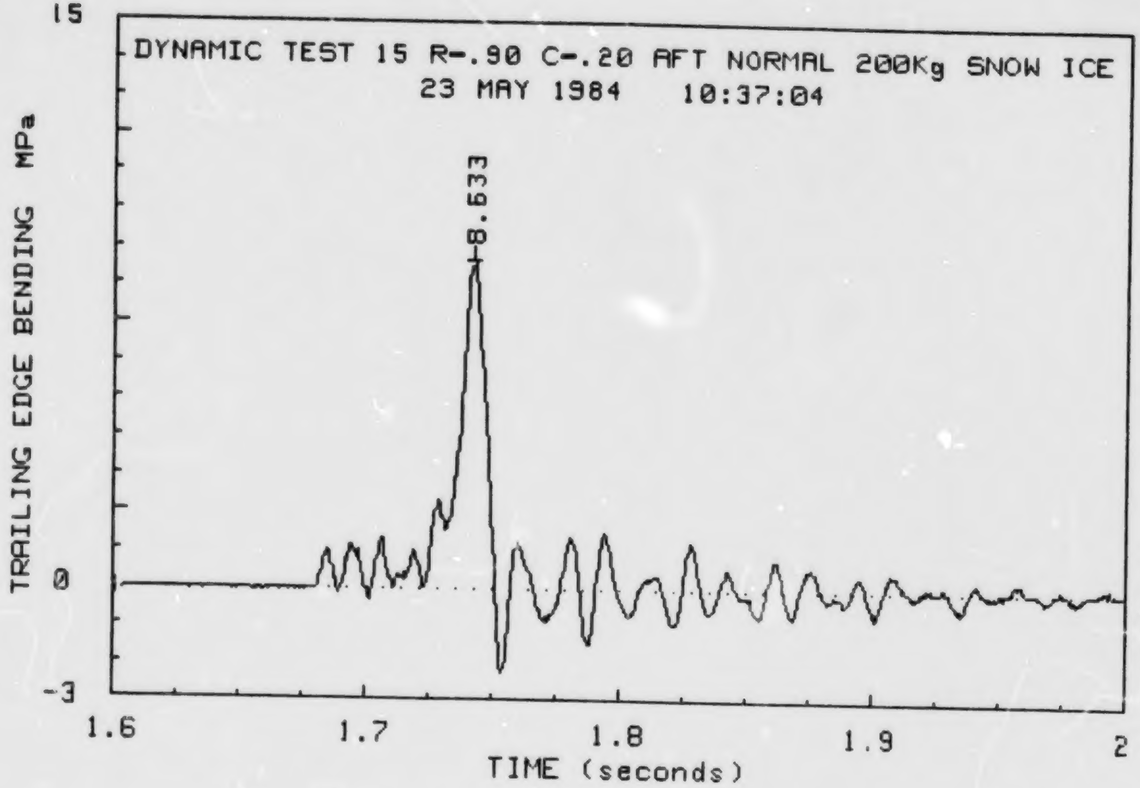


**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** CENTRE TORQUE DYNAMIC RESPONSE

**FIGURE No.** 3·3·5

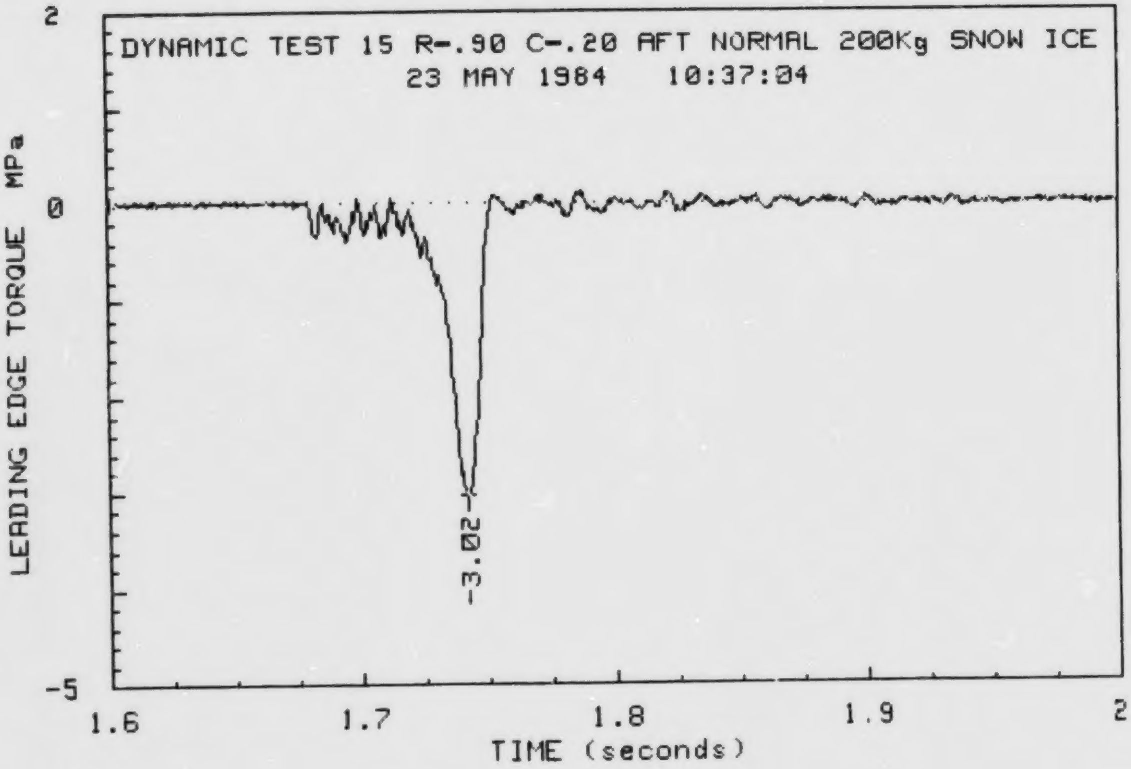


**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** **TRAILING EDGE BENDING DYNAMIC RESPONSE**

**FIGURE No.** **3·3·6**

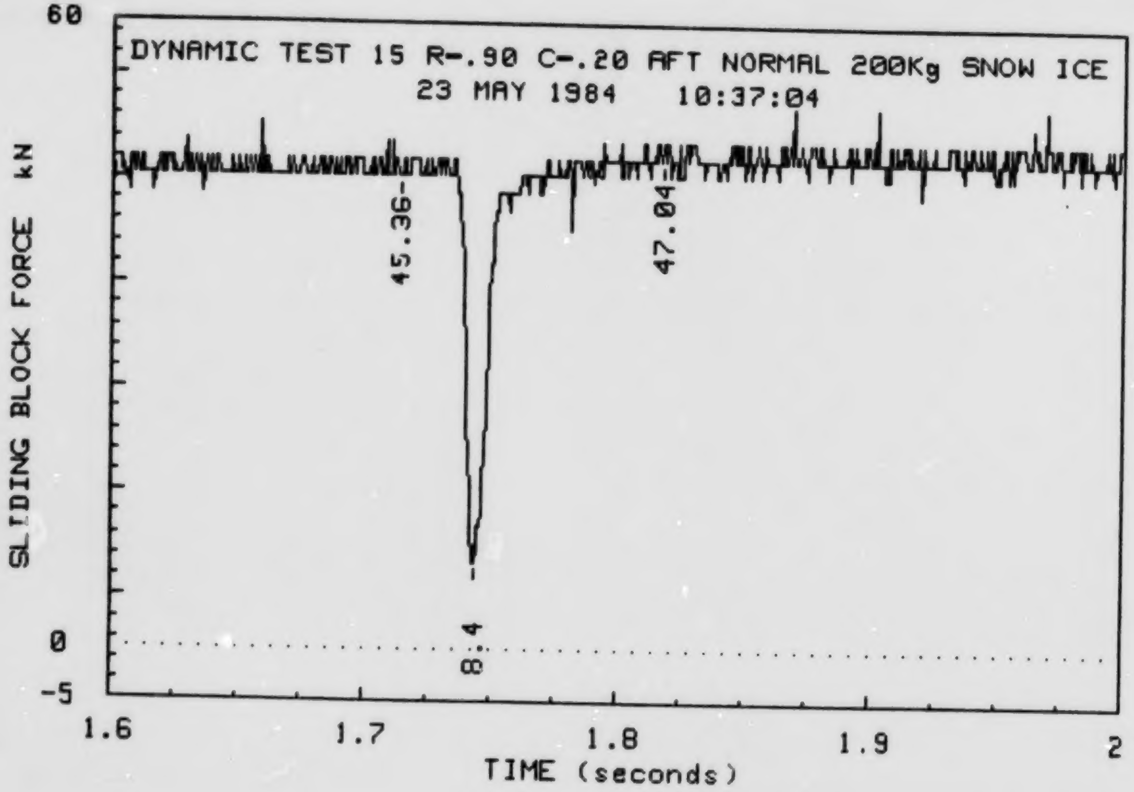


**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** LEADING EDGE TORQUE DYNAMIC RESPONSE

**FIGURE No.** 3·3·7



CANADIAN
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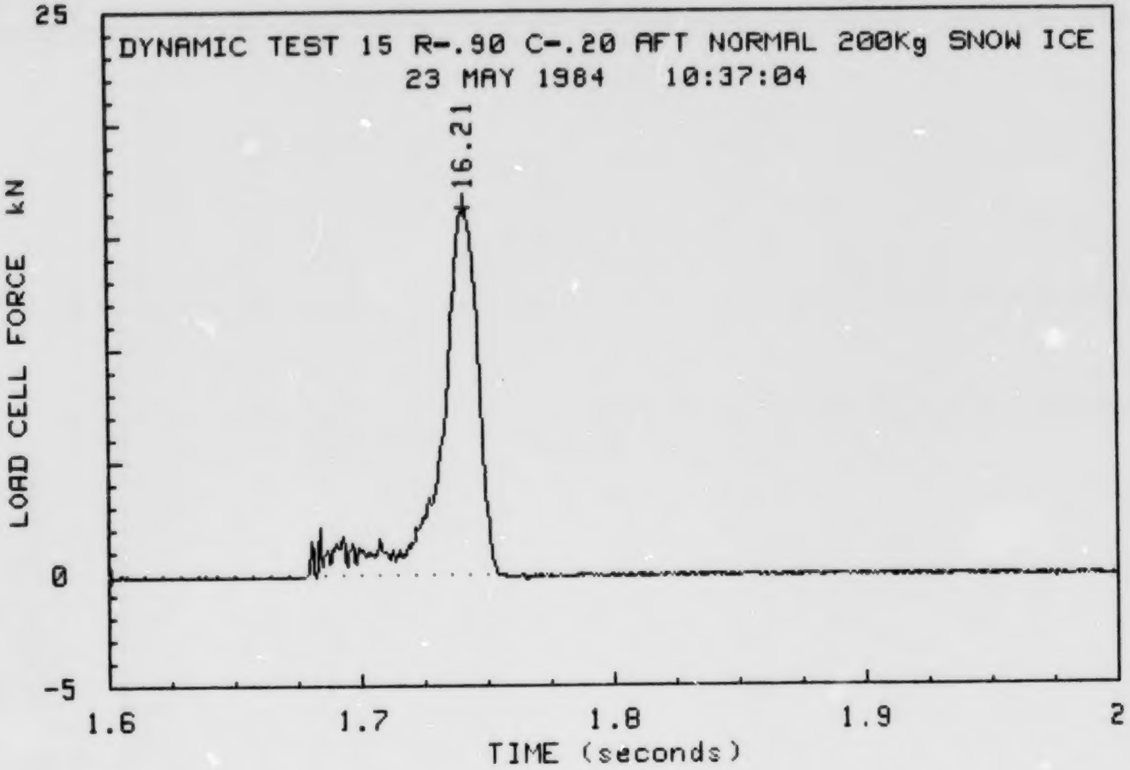
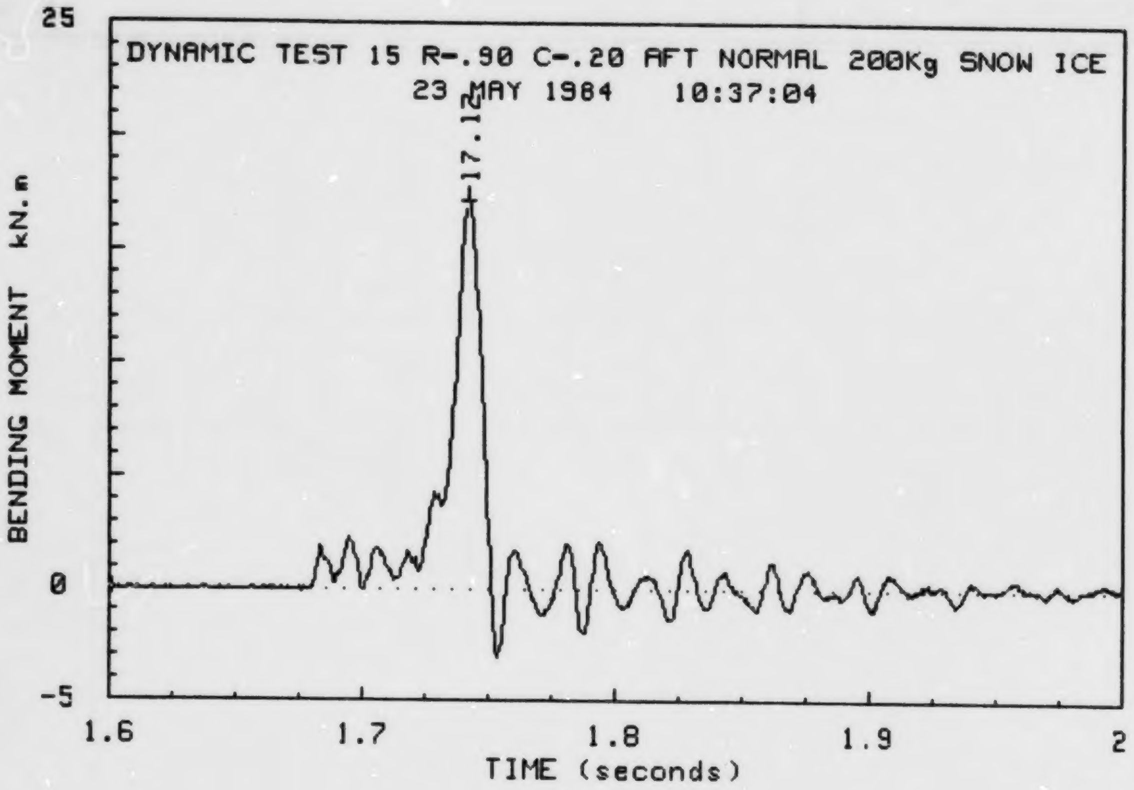
MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE: SLIDING BLOCK FORCE DYNAMIC RESPONSE

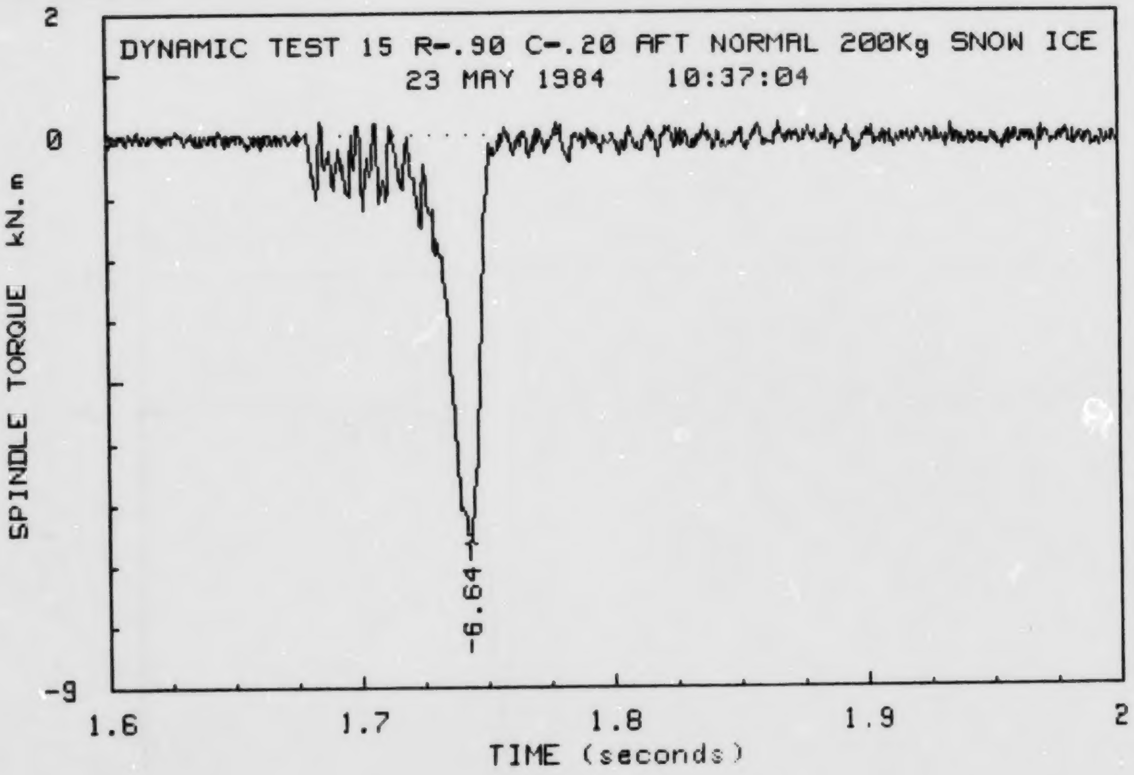
FIGURE No. 3·3·8



| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | **TITLE:** **LOAD APPLIED TO BLADE FOR DYNAMIC CALIBRATION** |
| | | **FIGURE No.** 3·3·9 |



| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | TITLE: **BENDING MOMENT CALCULATED FROM THE DYNAMIC RESPONSE** |
| | | FIGURE No. 3·3·10 |

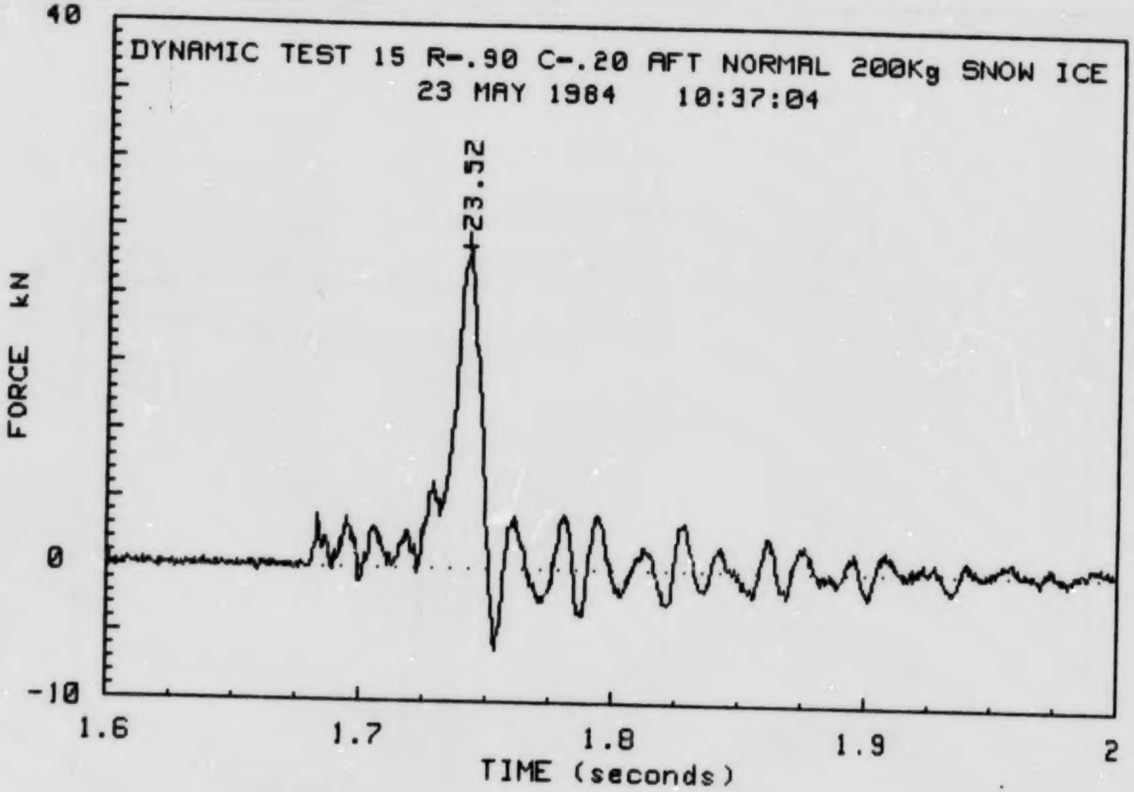


CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE PROPELLER
INTERACTION PARAMETERS

TITLE: SPINDLE TORQUE CALCULATED
FROM THE DYNAMIC RESPONSE

FIGURE No. 3·3·11

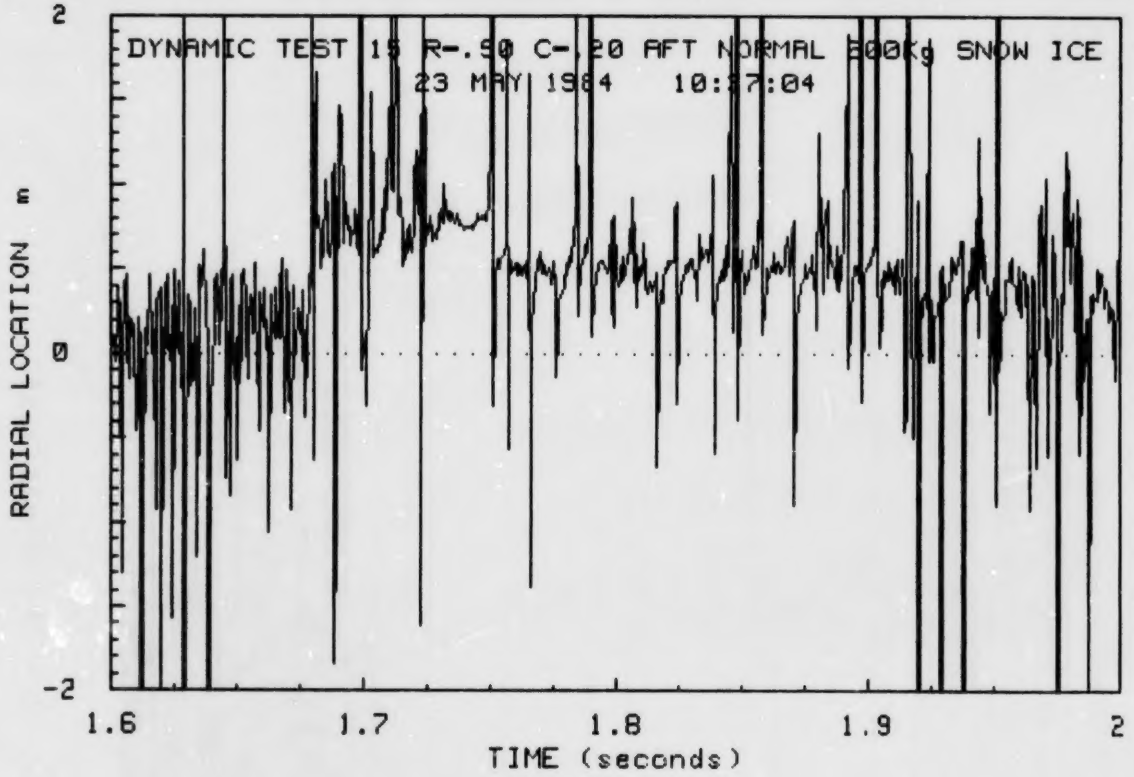


**CANADIAN MARINE DRILLING LIMITED**

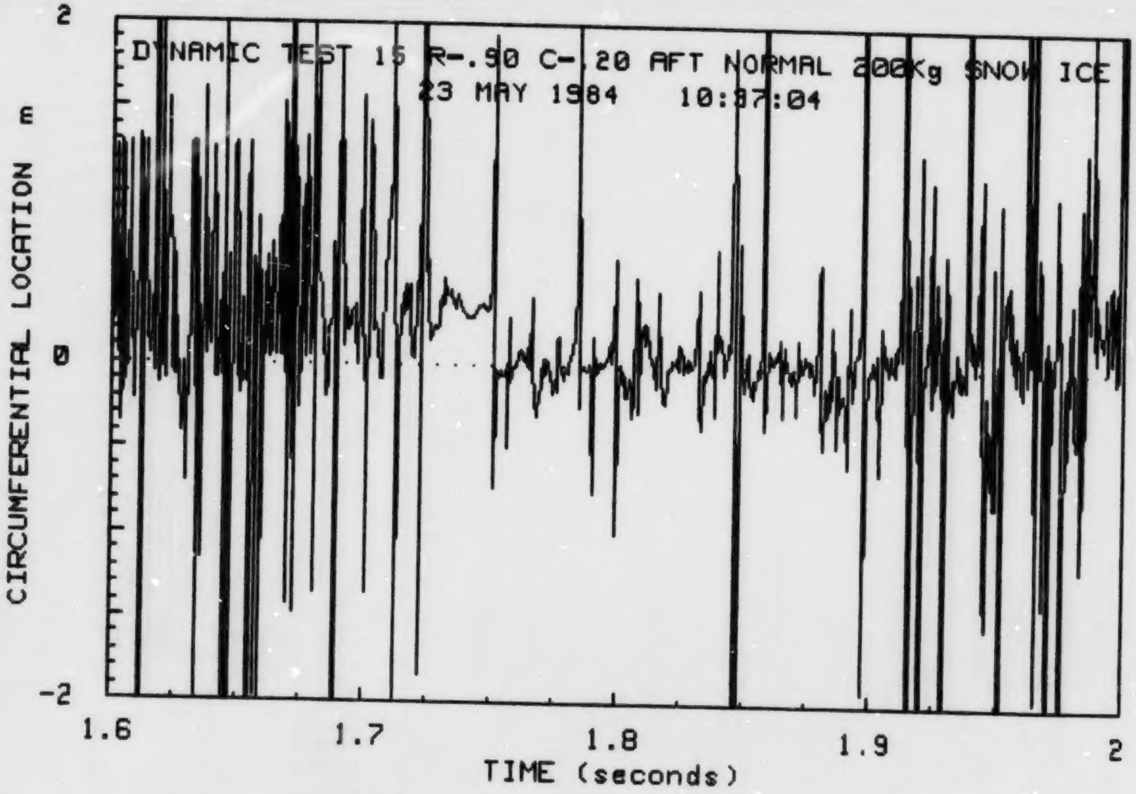
**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** **FORCE CALCULATED FROM THE DYNAMIC RESPONSE**

**FIGURE No.** 3·3·12



| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER<br>INTERACTION PARAMETERS | TITLE: RADIAL LOCATION OF LOAD CALCULATED DURING DYNAMIC LOADING<br>FIGURE No. 3·3·13 |



CANADIAN
MARINE
DRILLING
LIMITED

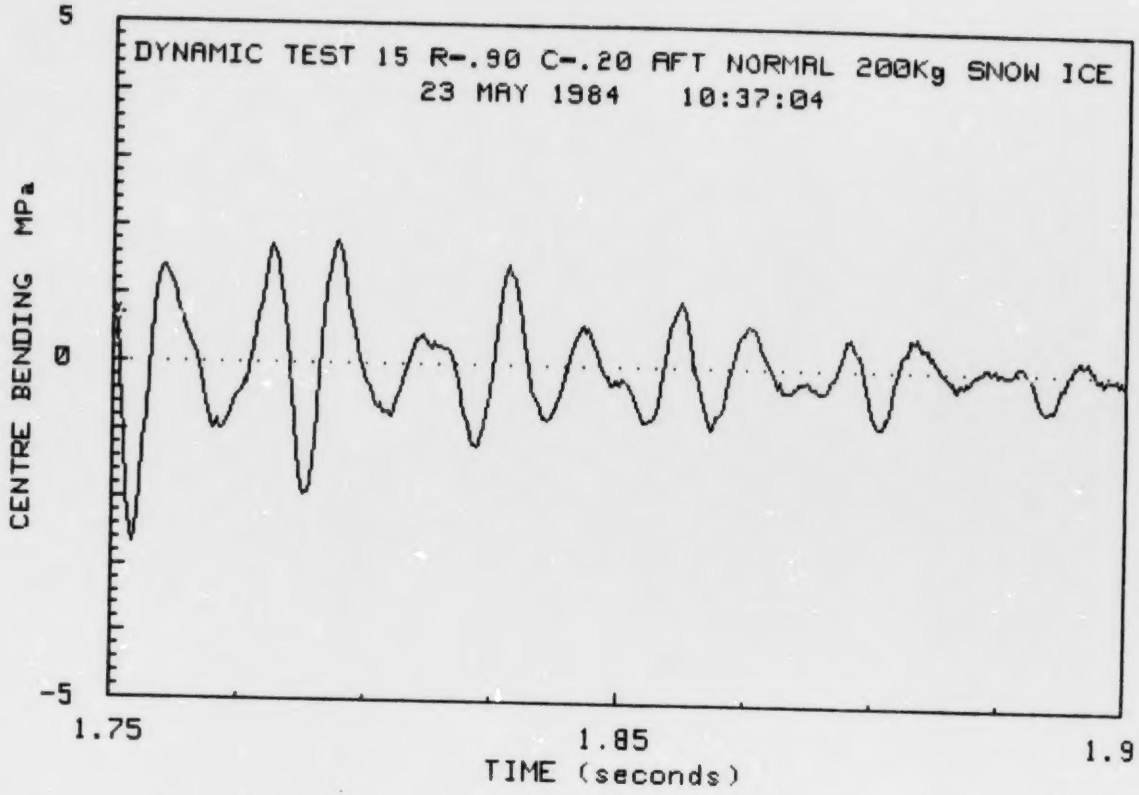
MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE: CIRCUMFERENTIAL LOCATION OF LOAD, CALCULATED DURING DYNAMIC LOADING

FIGURE No. 3·3·14

Changes in the signals, at a low average signal level, tend to cause the results of divisions performed by the computer to vary widely. It should be noted, however, that the predicted location is stable when the load is applied to the blade.

The dynamic calibration data is also used to measure the natural frequencies of vibration for the propeller blade in air. The natural frequencies are calculated by performing a Fast Fourier Transform (FFT) on the blade signals recorded during forced vibration of the blade. The time periods of the signals used to calculate the FFT are shown in Figures 3.3.15 and 3.3.17. The FFT for each of these signals are plotted in Figures 3.3.16 and 3.3.18.



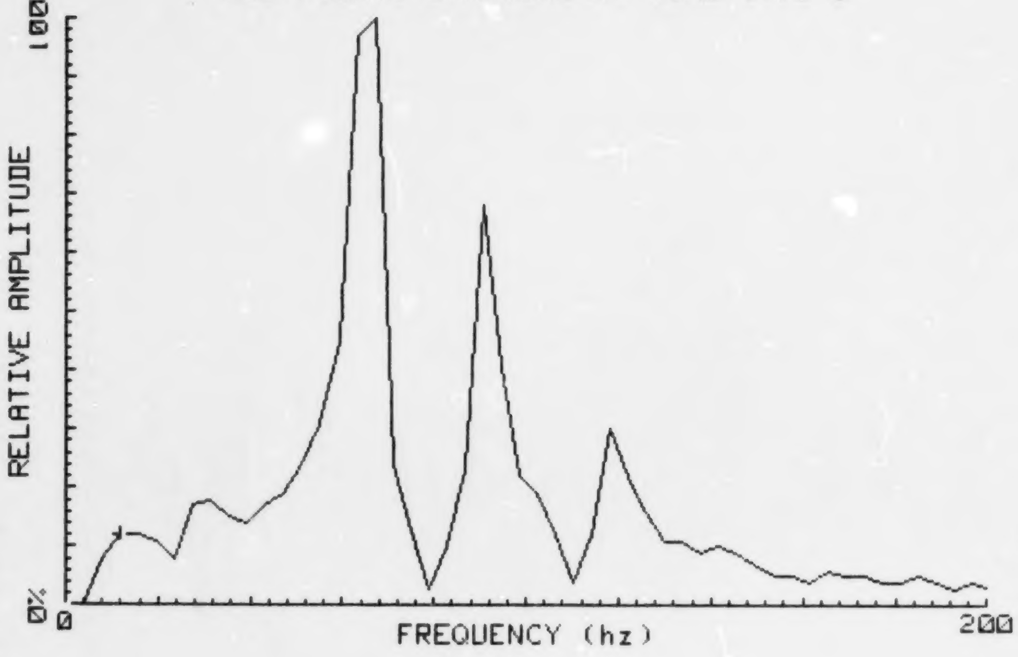
**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

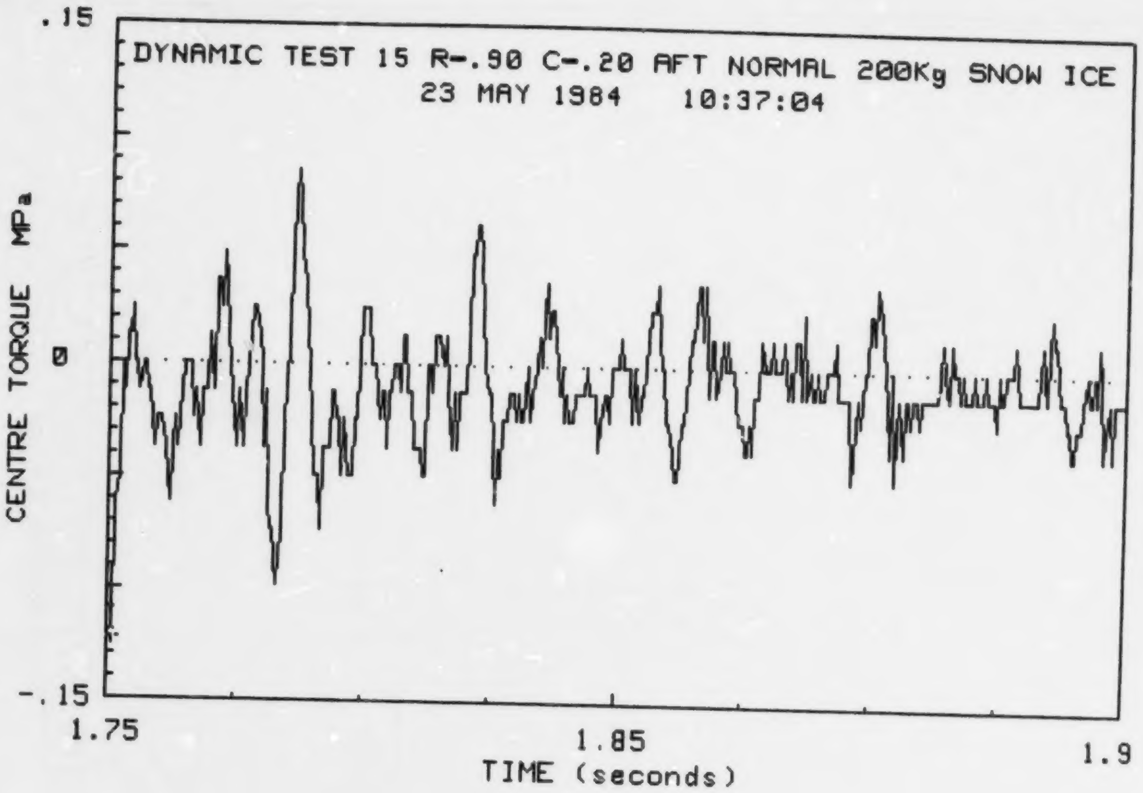
**TITLE: CENTRE BENDING SIGNAL USED FOR FFT CALCULATION**

**FIGURE No. 3·3·15**

DYNAMIC TEST 15 R=.90 C=.20 AFT NORMAL 200Kg SNOW ICE
FFT of CENTRE BENDING
MAXIMUM AMPLITUDE = 2.09E-02 MPa
512 POINTS STARTING AT TIME 1.75 s



| | | |
|---|---|---|
| **CANADIAN<br>MARINE<br>DRILLING<br>LIMITED** | **MEASUREMENT OF ICE PROPELLER<br>INTERACTION PARAMETERS** | TITLE:<br>**FFT OF CENTRE BENDING SIGNAL** |
| | | FIGURE No. 3·3·16 |

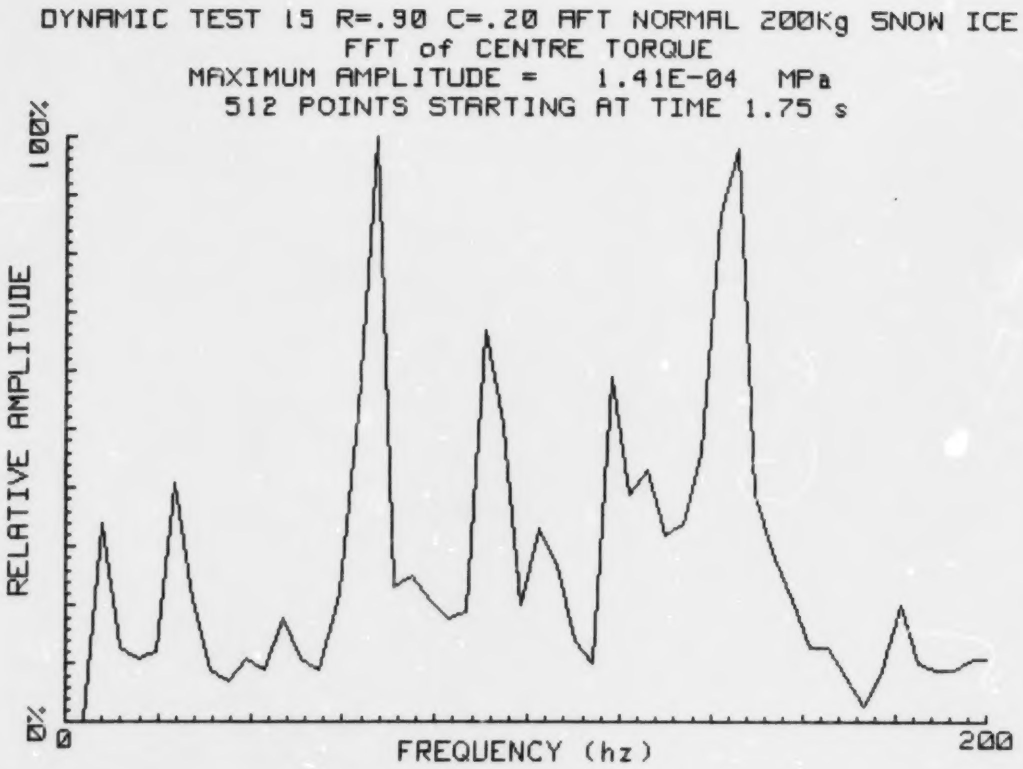


CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE PROPELLER
INTERACTION PARAMETERS

TITLE: CENTRE TORQUE SIGNAL
USED FOR FFT CALCULATION

FIGURE No. 3·3·17


DYNAMIC TEST 15 R=.90 C=.20 AFT NORMAL 200Kg SNOW ICE
FFT of CENTRE TORQUE
MAXIMUM AMPLITUDE = 1.41E-04 MPa
512 POINTS STARTING AT TIME 1.75 s

| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: FFT OF CENTRE TORQUE SIGNAL |
|---|---|---|
| | | FIGURE No. 3·3·18 |

# 4. CALIBRATION OF SLIDING BLOCK AND OTHER TRANSDUCERS

## 4.1 Sliding Block

### 4.1.1 Sliding Block Preparation

The sliding block assembly in the LIPS CPP system connects the propeller positioning yoke and yoke pin to the slot of the propeller blade carrier. Since the blade carrier slot is offset from the pitch centre of the blade, any linear motion of the yoke pin produces a pitch rotation in the blade carrier.

Any forces needed to hold the blade at a specific pitch location are transferred from the inside slot face of the blade carrier to the contacting face of the sliding block. In order to measure the magnitude of these pitch holding forces during ice interactions, the two contacting faces of the sliding block were instrumented.

### 4.1.2 Sliding Block Modifications

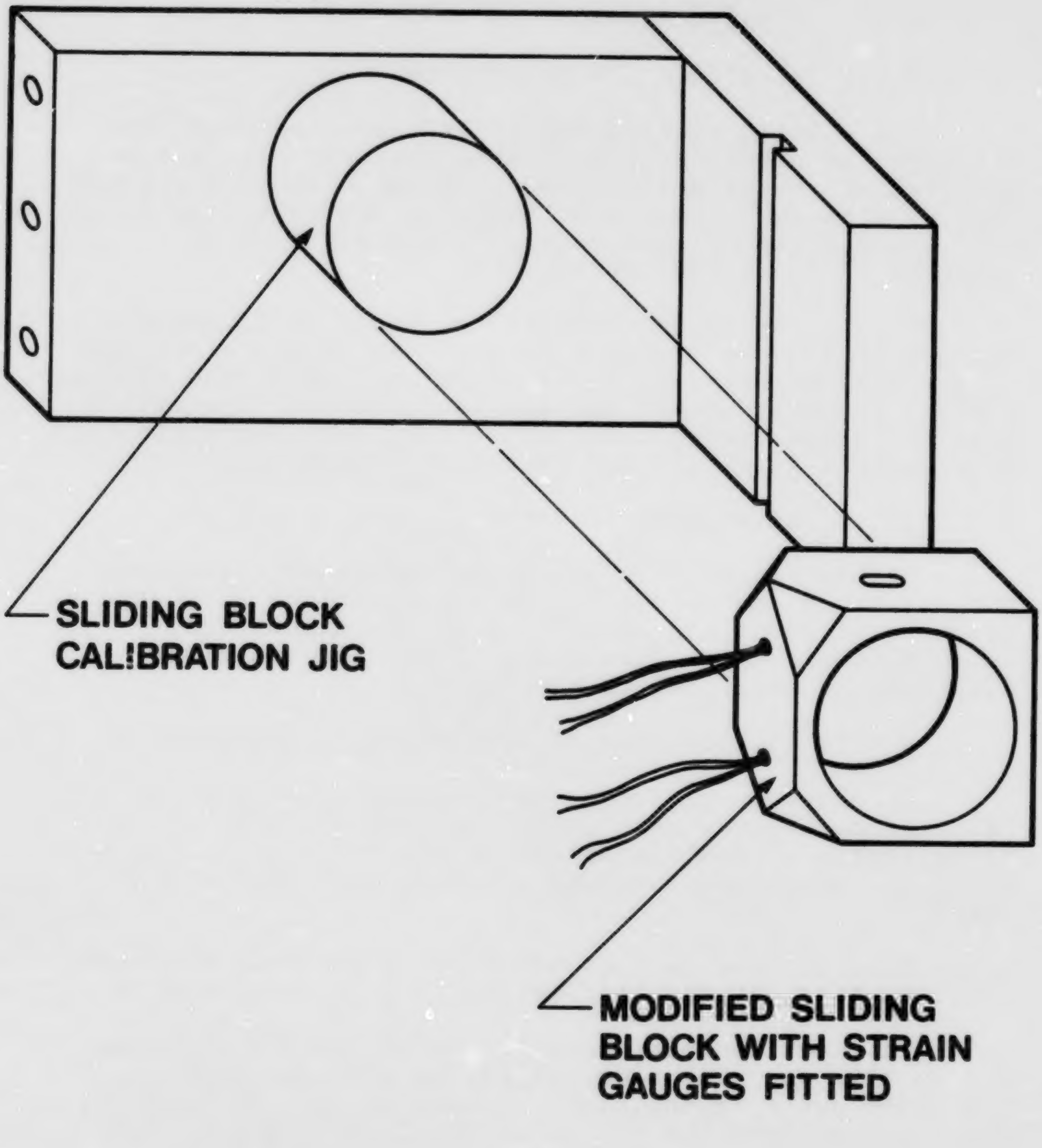
Strain gauges were chosen as the sensing elements for measuring the forces on the sliding block. To ensure proper attachment and protection of the gauges and associated wiring, modification of the sliding block was required, as described in Section 2.2.

### 4.1.3 Instrumented Sliding Block Calibration Jig

In order to calibrate the instrumented block a calibration jig was made up to simulate the yoke pin and blade carrier. The dimensions of the calibration jig were based on "as-fitted" information from the manufacture (LIPS).

This jig was made of SAE 4340, high yield strength steel to take the required calibration loads of 450 KN.

The machined pin plate of the jig measured 280 mm * 212 mm * 50 mm. The machined 126 mm diameter pin protruded out from the plate surface 69 mm. To hold the plate up and keep the pin on the horizontal plane, two side plates were bolted to the main pin plate as illustrated in Figure 4.1.1. Slots were provided in the side plates for a sliding block retention plate.


SLIDING BLOCK CALIBRATION JIG
MODIFIED SLIDING BLOCK WITH STRAIN GAUGES FITTED

CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE: SLIDING BLOCK CALIBRATION SET-UP

FIGURE No. 4·1·1

The sliding block was placed over the pin with one of its gauged load bearing surfaces upwards. Load was then applied to this face from above, using a flat interface steel plate in series with a standard load cell. This final calibration configuration is illustrated in the photographs taken at the University of Calgary, Figures 4.3.1 to 4.3.4.

Test facilities at both the University of Calgary and the Southern Alberta Institute of Technology were used for the calibration program. The following sections will detail the equipment used and the results.

### 4.2 Southern Alberta Institute Of Technology (SAIT) Calibration

| | |
|---|---|
| Date: | 84-04-30 |
| Time: | 7:00 pm. to 11:00 pm. |
| Location: | SAIT Materials Testing Lab<br>Room #1719 |
| Load Machine: | TINIUS OLSEN Testing Frame |
| Load Measurement: | Dial Gauge from Load Frame |
| Signal Conditioning: | Vishay Series 2100 Stain Gauge Amplifier |
| Bridge Excitation: | 10 Volts D.C. |
| Amplifier Gain: | 1000 |

After putting the sliding block onto the calibration jig in the load frame, the strain gauge wires were connected to the signal conditioner in a full bridge configuration. The two gauges on the face to be loaded were wired in opposite arms of the bridge so that the signals would be summed in the amplifier.

Amplifier output voltage was offset to zero in the unloaded condition. Force was then applied to a 20 mm thick, rectangular plate placed over the sliding block loading face. Output voltages were then monitored in relation to applied load.

The loading test frame operated in two ranges; one 0 to 350 KN and one 0 to 900 KN. It was found that when ranges were changed during calibration, equal load reading in the two ranges produced strain gauge output voltages some 20% different from one another. This observation,

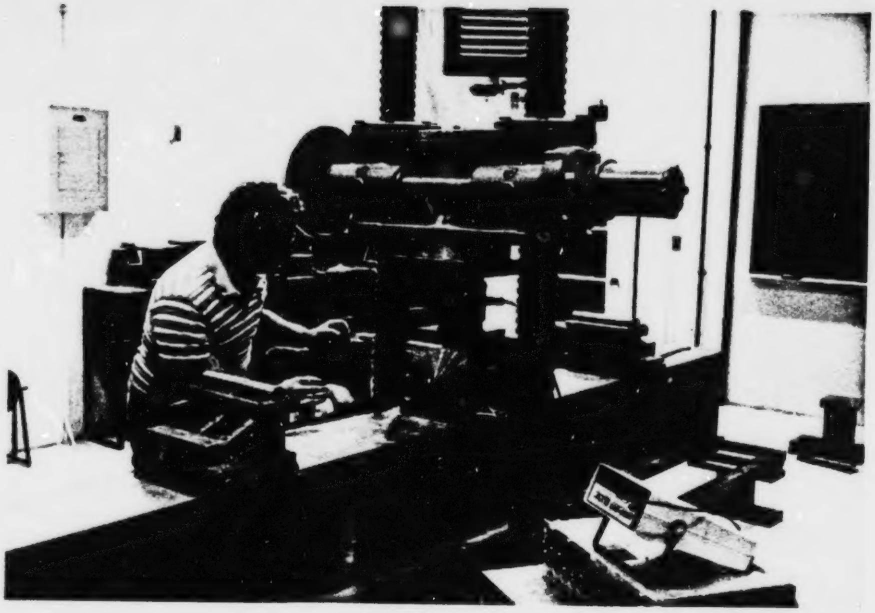


FIGURE 4.3.1
UNIVERSITY OF CALGARY LOADING FRAME - FRONT SIDE VIEW

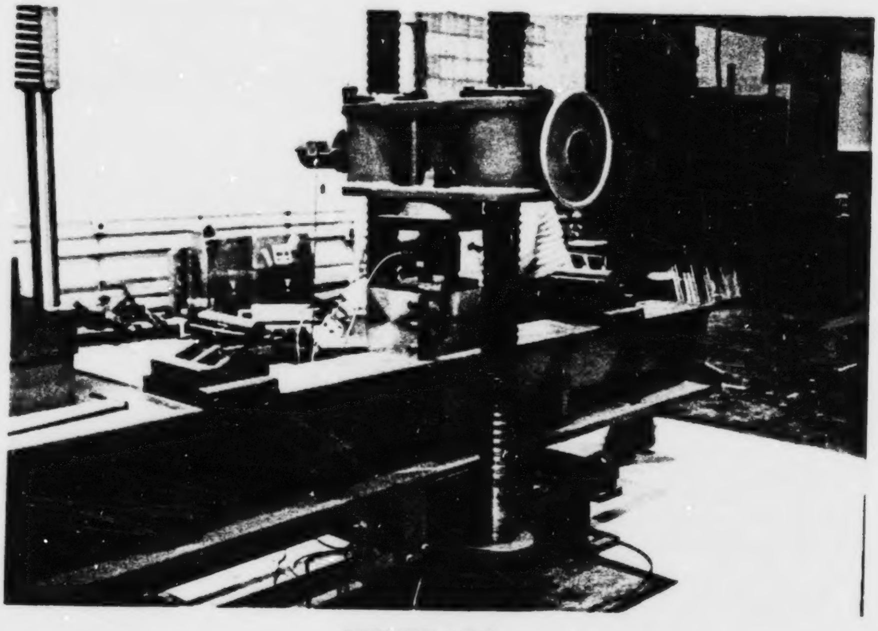


FIGURE 4.3.2.
UNIVERSITY OF CALGARY LOADING FRAME - BACK SIDE VIEW

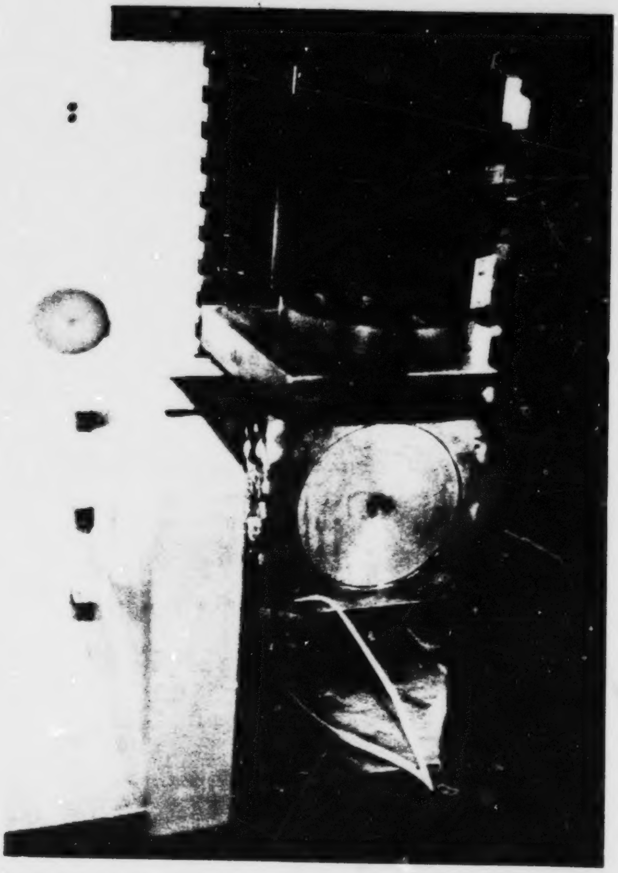


FIGURE 4.3.3
SLIDING BLOCK CALIBRATION JIG WITH SLIDING BLOCK AND LOAD CELL IN PLACE ON LOADING FRAME

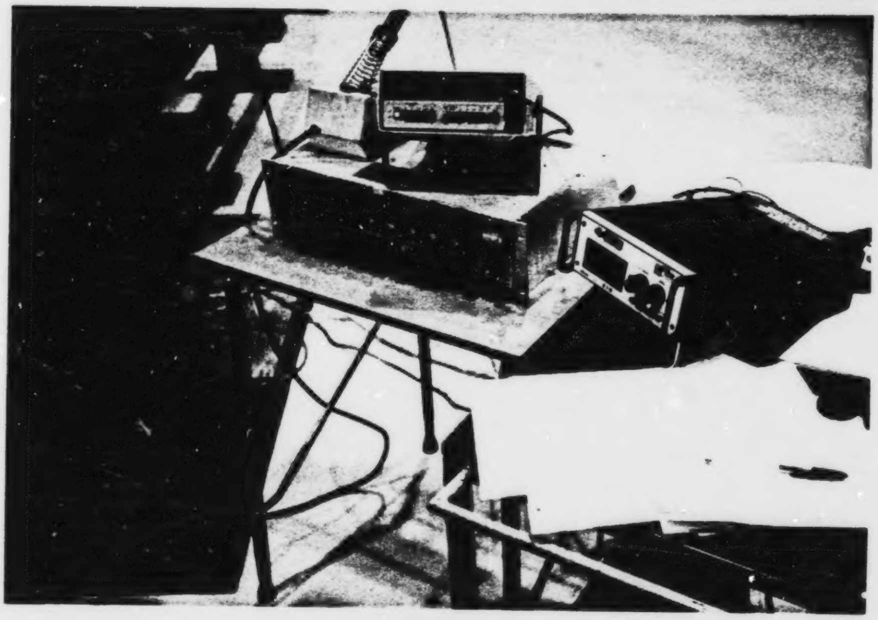


FIGURE 4.3.4
STRAIN GAUGE AMPLIFIER AND READOUT INSTRUMENTATION

| | | |
|---|---|---|
| CANMAR<br>CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE:<br>FIGURE No. |

coupled with the fact that the last load frame calibration had been carried out in 1980, recommended the use of a more accurate testing arrangement.

## 4.3 University Of Calgary (U of C) Calibration

The testing facility at the University of Calgary could provide the required performance.

Date: 84-05-02 to 05-03
Location: University of Calgary - Materials Testing Lab.
Load Machine: AMSLER 76/57 Test Machine
Load Measurement: LEBOW Products Load Cell Model 3156-102, S/N 2109
Signal Conditioning: VISHAY Series 2100 Strain Gauge Amplifier
Bridge Excitation: 10 Volts DC
Amplifier Gain: 1000

The sliding block and calibration jig were set into the load framework. A piece of 38 mm steel plate and the load cell were then placed on the sliding block loading face. The assembly was centered and the moveable reaction head of the load frame lowered onto the load cell. Figure 4.3.1 through 4.3.4 show the calibration equipment set-up at U of C .

Several load cycles were performed to measure the repeatability and stability of readings. It was found that a hole through the center of the original 38 mm plate used, tended to load the sliding block face unevenly and adversely influenced repeatability. To correct this, a new 38 mm thick force 'plate' was fabricated with parallel machined faces.

Also noted was a differential signal from the two gauges on the loaded face of the sliding block. This was reduced by oiling the pin/sliding block faces. Since this better simulated the oil lubricated propeller blade system, calibrations were made with a lubricated pin assembly.

Quarter bridge readings were made on the non-loaded gauges during testing. Amplifier output voltages did not change more than 0.005 volts over the range of 0 to 450 KN load on the loaded side of the sliding block. This confirmed that load applied to one side of the block did not produce strain in the opposite face and that all four gauges could be used in a two active arm full bridge configuration.

When the strain gauges were installed, one load face was wired using red and white twisted pairs and the opposite load face strain gauges were connected to black and white twisted pair wires. These colour codes were used to identify the face of the sliding block being loaded for each calibration load cycle.

For redundancy purposes, the full bridge circuit was brought out to the amplifier input as two complete half bridge circuits using six wires. The two, 3-wire half bridge circuits were identified as Sa and Sb. Circuit configurations for the actual field installation were kept identical to this calibration wiring.

Final Calibration Load Cycles :

| TEST NO. | CIRCUIT WIRING | FACE LOADED |
|---|---|---|
| 11B | Full Bridge | Red - White |
| 11C | Full Bridge | Red - White |
| 12A | Full Bridge | Black - White |
| 12B | Full Bridge | Black - White |
| 13 | Sb Half Bridge | Black - White |
| 14 | Sa Half Bridge | Black - White |
| 15 | Sa Half Bridge | Red - White |
| 16 | Sb Half Bridge | Red - White |

Result tables and graphs of these calibration runs are included on the following pages, Tables 4.3.1 to 4.3.9(B) and Figures 4.3.5 to 4.3.13.

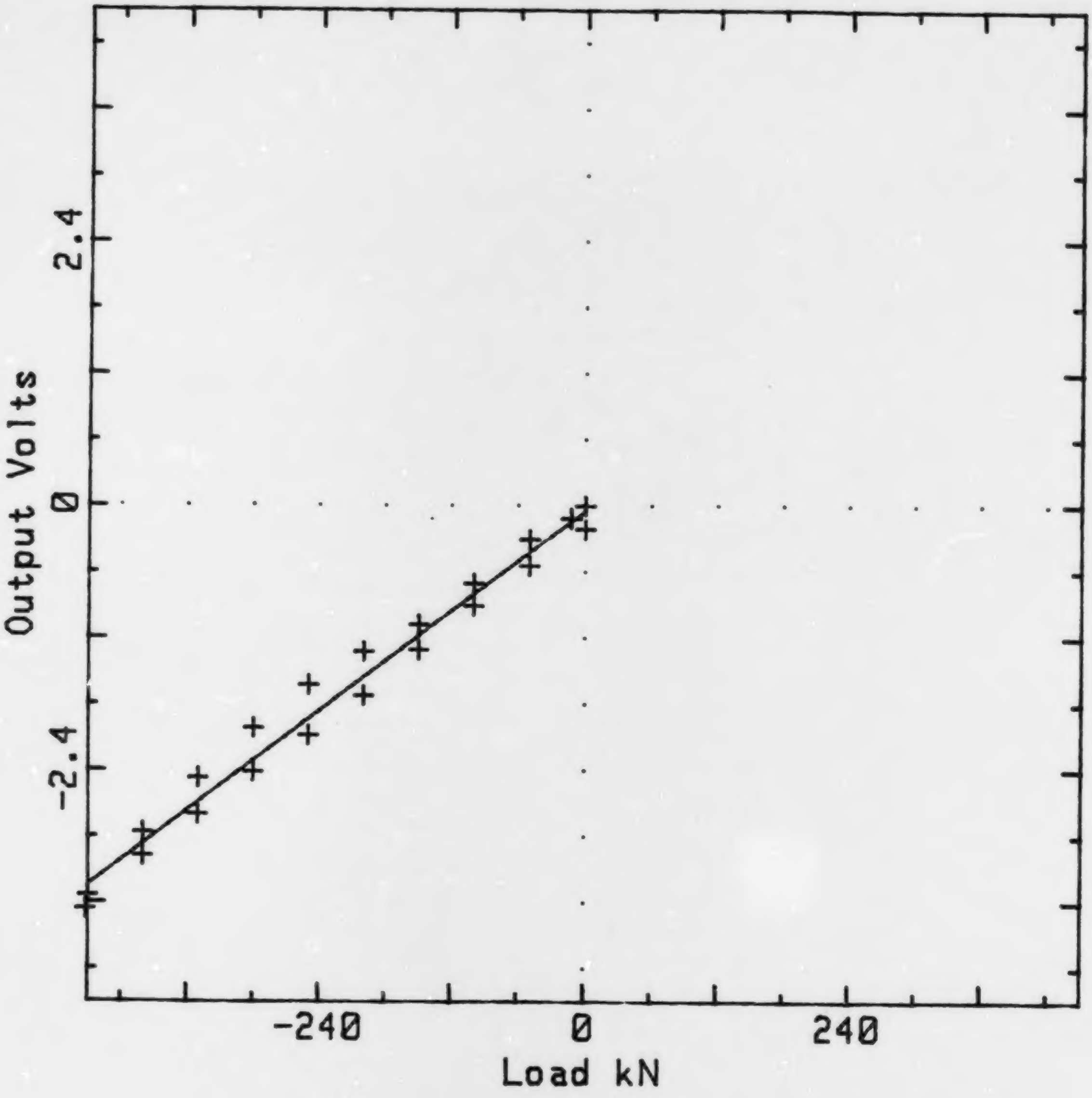
## 4.4 Sliding Block Wurmlinger Calibration

The data obtained during the static and dynamic calibrations on the John Wurmlinger was gathered to check the applicability of the sliding block static calibration performed in Calgary. Since the output signal of the block was dependent on such things as pin lubrication and surface finish of the mating parts; an in-situ calibration was considered to be a necessity. The other reason for gathering the sliding block calibration signal was as a means to measure the friction in the hub bearings (see Section 9 for a discussion of the friction in the blade carrier bearings).

In order to determine the possible friction in the system, a table of predicted sliding block loads versus applied load, point and case was generated. The predicted sliding block loads for an input force of 1 kN at the

```
                    Test Number 11 B
                    Load On Red-White Side
                    Full Bridge
                    Excitation = 10 V     Gain = 1000

X COORDINATE: Load kN
Y COORDINATE: Output Volts

      I          X COORD.          Y COORD.          COMMENT

      1         0.0000E+00       -1.5000E-02
      2        -1.2800E+01       -1.2700E-01
      3        -5.0000E+01       -3.1800E-01
      4        -1.0000E+02       -7.1800E-01
      5        -1.5000E+02       -1.0940E+00
      6        -2.0000E+02       -1.3400E+00
      7        -2.5000E+02       -1.6400E+00
      8        -3.0000E+02       -2.0290E+00
      9        -3.5000E+02       -2.4790E+00
     10        -4.0000E+02       -2.9700E+00
     11        -4.5000E+02       -3.5400E+00
     12        -4.5200E+02       -3.6630E+00
     13        -4.0000E+02       -3.1790E+00
     14        -3.5000E+02       -2.8020E+00
     15        -3.0000E+02       -2.4210E+00
     16        -2.5000E+02       -2.0890E+00
     17        -2.0000E+02       -1.7320E+00
     18        -1.5000E+02       -1.3150E+00
     19        -1.0000E+02       -9.1500E-01
     20        -5.0000E+01       -5.5000E-01
     21         2.2000E-01       -2.1800E-01

 ORDER OF REGRESSION = 1
 STANDARD DEVIATION  = 1.6432199E-01

 Y = 7.559858E-03 * X^ 1 -4.878172E-02
```

| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 11B, DATA |
|---|---|---|
| | | TABLE 4·3·1 |

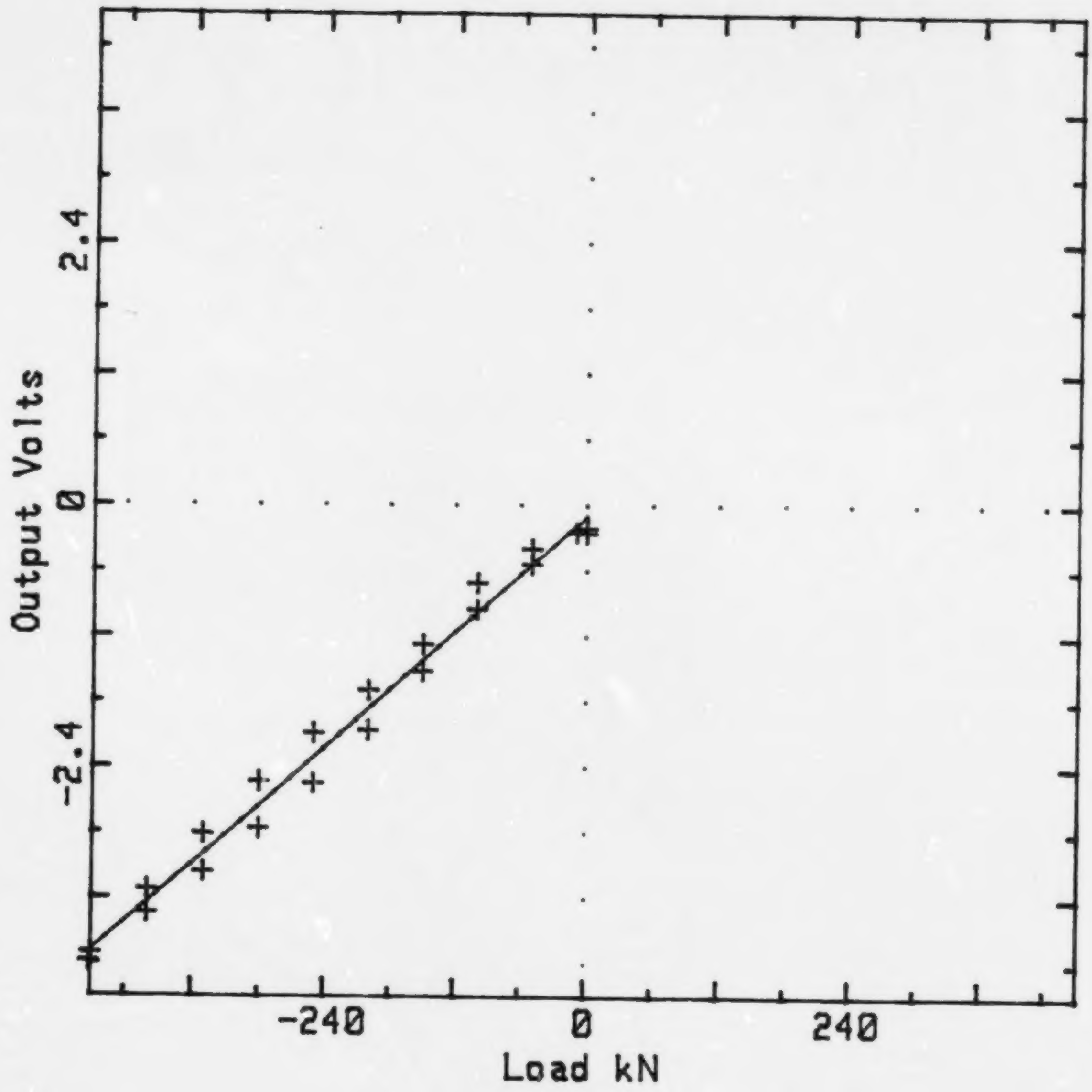


Test Number 11 B
Load On Red-White Side
Full Bridge
Excitation = 10 V     Gain = 1000

| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 11B, PLOT<br>FIGURE No. 4·3·5 |
|---|---|---|

```
                 Test Number 11 C
                 Load On Red-White Side
                 Full Bridge
                 Excitation = 10 V     Gain = 1000

X COORDINATE: Load kN
Y COORDINATE: Output Volts

      I         X COORD.         Y COORD.          COMMENT

      1        0.0000E+00      -2.2200E-01
      2       -9.5000E+00      -2.6000E-01
      3       -5.0000E+01      -4.0800E-01
      4       -1.0000E+02      -7.2300E-01
      5       -1.5000E+02      -1.2920E+00
      6       -2.0000E+02      -1.7130E+00
      7       -2.5000E+02      -2.1000E+00
      8       -3.0000E+02      -2.5430E+00
      9       -3.5000E+02      -3.0190E+00
     10       -4.0000E+02      -3.5300E+00
     11       -4.5000E+02      -4.1100E+00
     12       -4.5160E+02      -4.1890E+00
     13       -4.0000E+02      -3.7430E+00
     14       -3.5000E+02      -3.3630E+00
     15       -3.0000E+02      -2.9630E+00
     16       -2.5000E+02      -2.5520E+00
     17       -2.0000E+02      -2.0700E+00
     18       -1.5000E+02      -1.5320E+00
     19       -1.0000E+02      -9.6000E-01
     20       -5.0000E+01      -5.4400E-01
     21        0.0000E+00      -2.5800E-01

ORDER OF REGRESSION = 1
STANDARD DEVIATION  = 1.6360168E-01

Y = 8.863980E-03 * X^ 1 -1.003666E-01
```

| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 11C, DATA<br>TABLE 4·3·2 |
|---|---|---|

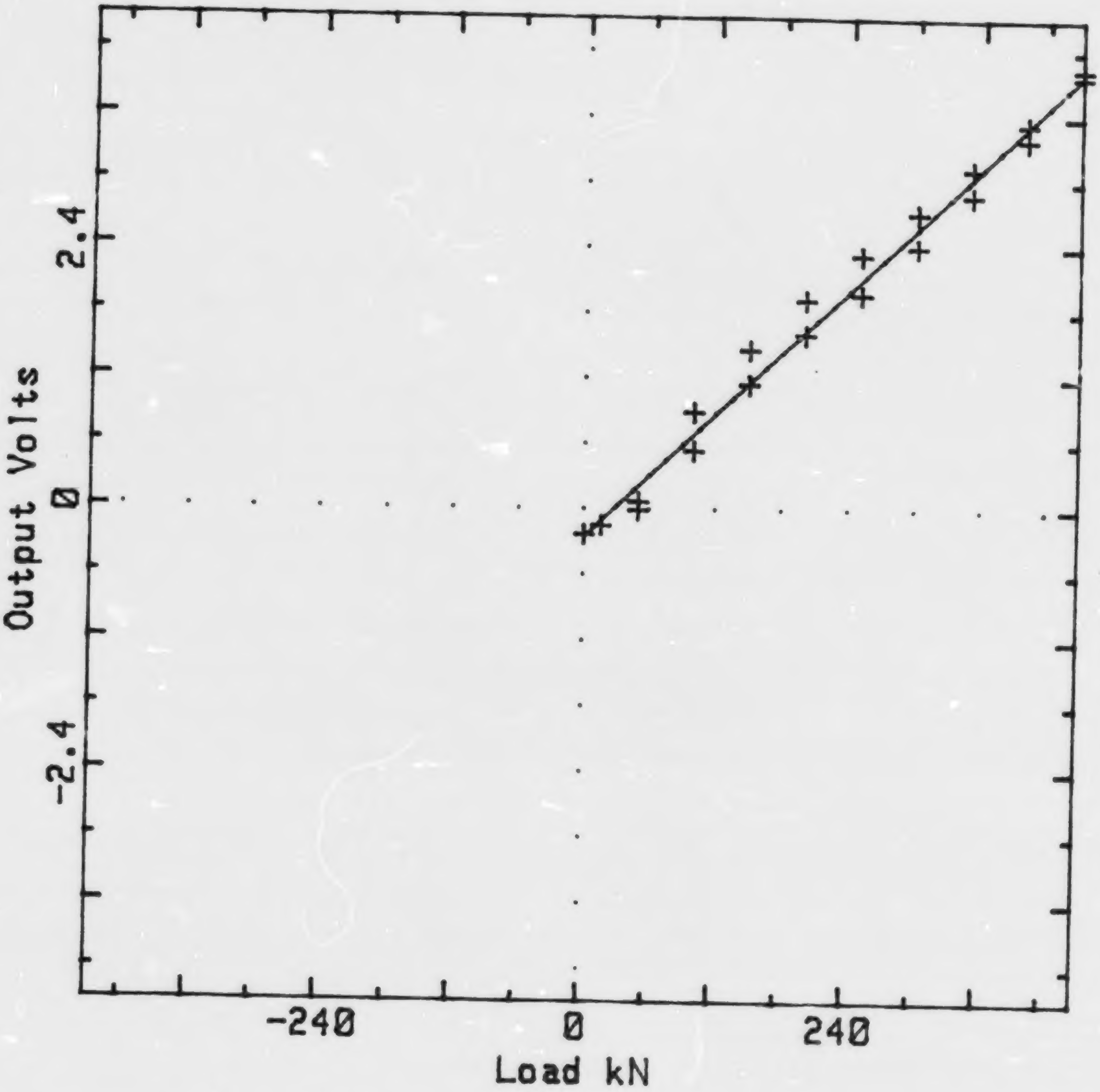


Test Number 11 C
Load On Red-White Side
Full Bridge
Excitation = 10 V Gain = 1000

| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 11C, PLOT<br>FIGURE No. 4·3·6 |
|---|---|---|

```
                    Test Number 12 A
                    Load On Black-White Side
                    Full Bridge
                    Excitation = 10 V      GAIN = 1000

          X COORDINATE: Load kN
          Y COORDINATE: Output Volts

                I       X COORD.         Y COORD.        COMMENT

                1     0.0000E+00      -2.4900E-01
                2     1.6000E+01      -1.6300E-01
                3     5.0000E+01      -2.0000E-02
                4     1.0000E+02       5.3000E-01
                5     1.5000E+02       1.1400E+00
                6     2.0000E+02       1.6000E+00
                7     2.5000E+02       1.9700E+00
                8     3.0000E+02       2.4030E+00
                9     3.5000E+02       2.8800E+00
               10     4.0000E+02       3.4000E+00
               11     4.5000E+02       3.9800E+00
               12     4.5000E+02       4.0450E+00
               13     4.0000E+02       3.5390E+00
               14     3.5000E+02       3.1170E+00
               15     3.0000E+02       2.7090E+00
               16     2.5000E+02       2.3190E+00
               17     2.0000E+02       1.9090E+00
               18     1.5000E+02       1.4500E+00
               19     1.0000E+02       8.7900E-01
               20     5.0000E+01       5.6000E-02
               21     0.0000E+00      -2.4700E-01

           ORDER OF REGRESSION = 1
           STANDARD DEVIATION  = 1.5720606E-01

           Y = 9.496046E-03 * X^ 1 -2.684353E-01
```

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 12A, DATA |
| | | TABLE 4·3·3 |



Test Number 12 A
Load On Black-White Side
Full Bridge
Excitation = 10 V GAIN = 1000

**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 12A, PLOT**

**FIGURE No. 4·3·7**

```
               Test Number 12 B
               Load On Black-White Side
               Full Bridge
               Excitation = 10 V      GAIN = 1000

      X COORDINATE: Load kN
      Y COORDINATE: Output Volts

           I        X COORD.         Y COORD.         COMMENT

           1       0.0000E+00      -2.4200E-01
           2       0.0000E+00      -2.4700E-01
           3       2.0100E+01      -1.3300E-01
           4       5.0000E+01      -8.9000E-02
           5       1.0000E+02       2.0200E-01
           6       1.5000E+02       7.0800E-01
           7       2.0000E+02       1.0880E+00
           8       2.5000E+02       1.4560E+00
           9       3.0000E+02       1.9100E+00
          10       3.5000E+02       2.4180E+00
          11       4.0000E+02       2.9750E+00
          12       4.5000E+02       3.5760E+00
          13       4.5030E+02       3.6440E+00
          14       4.0000E+02       3.1210E+00
          15       3.5000E+02       2.6800E+00
          16       3.0000E+02       2.2330E+00
          17       2.5000E+02       1.7870E+00
          18       2.5000E+02       1.7910E+00
          19       3.0000E+02       2.2890E+00
          20       3.5000E+02       2.7090E+00
          21       4.0000E+02       3.1540E+00
          22       4.5000E+02       3.6730E+00
          23       4.5000E+02       3.6850E+00
          24       4.0000E+02       3.1480E+00
          25       3.5000E+02       2.7950E+00
          26       3.0000E+02       2.2370E+00
          27       2.5000E+02       1.8040E+00
          28       2.0000E+02       1.3520E+00
          29       1.5000E+02       8.5300E-01
          30       1.0000E+02       4.0000E-01
          31       5.0000E+01      -3.0000E-03
          32       0.0000E+00      -2.2700E-01

       ORDER OF REGRESSION = 1
       STANDARD DEVIATION  = 1.4710900E-01

       Y = 8.825180E-03 * X^ 1 -4.385774E-01
```

CANADIAN
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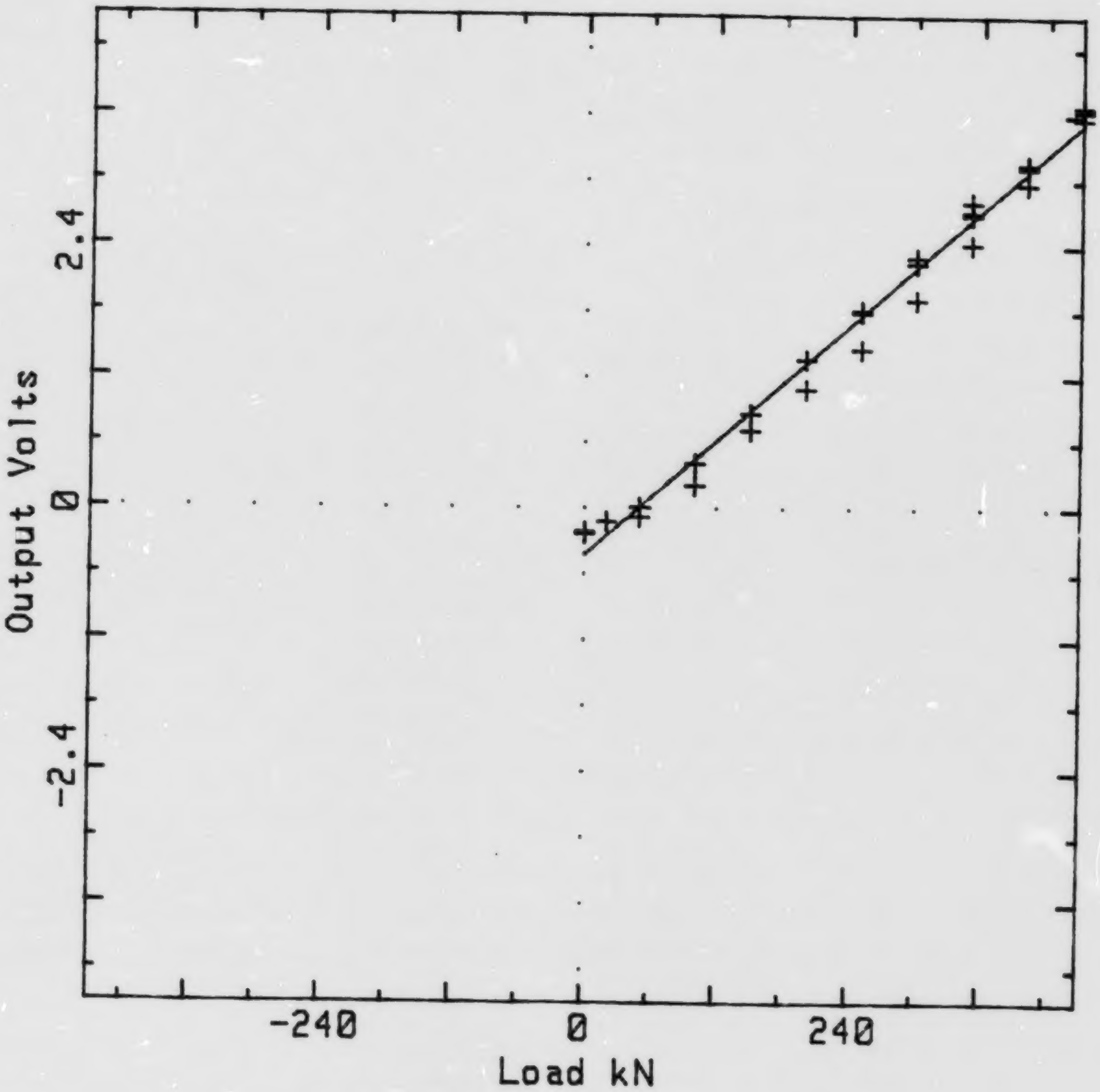
LIMITED

MEASUREMENT OF ICE
PROPELLER INTERACTION
PARAMETERS

TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 12B, DATA

TABLE 4·3·4



Test Number 12 B

Load On Black-White Side

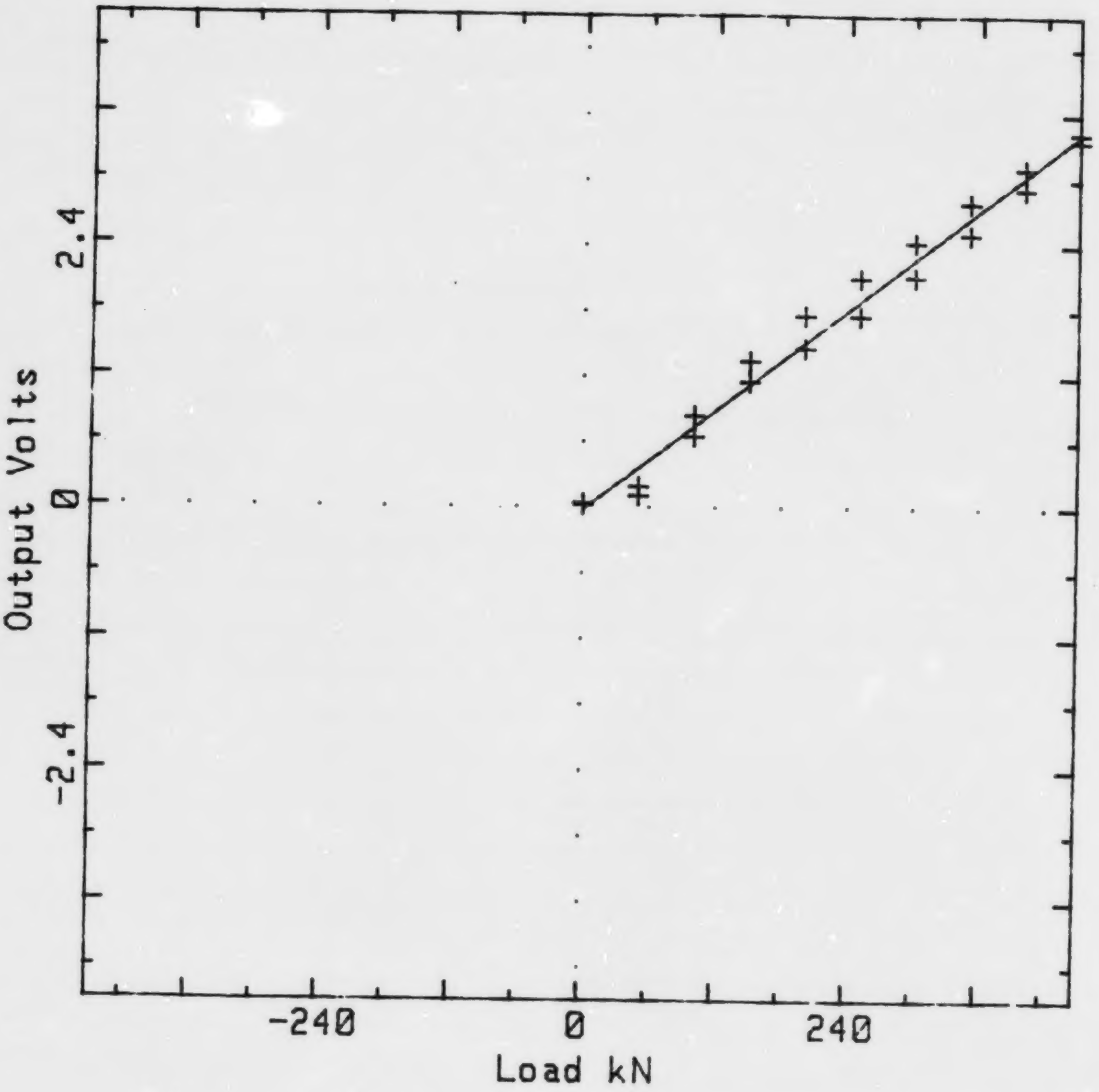
Full Bridge

Excitation = 10 V GAIN = 1000

| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE: U OF C SLIDING BLOCK<br>CALIBRATION TEST 12B,<br>PLOT<br>FIGURE No. 4·3·8 |
|---|---|---|

```
                 Test Number 13
                 Load On Black-White Side
                 Half Bridge
                 Excitation = 10 V      GAIN = 1000

X COORDINATE: Load kN
Y COORDINATE: Output Volts

        I          X COORD.         Y COORD.         COMMENT

        1        0.0000E+00       1.0000E-02
        2        5.0000E+01       9.9000E-02
        3        1.0000E+02       6.4400E-01
        4        1.5000E+02       1.1440E+00
        5        2.0000E+02       1.4540E+00
        6        2.5000E+02       1.7510E+00
        7        3.0000E+02       2.1100E+00
        8        3.5000E+02       2.5000E+00
        9        4.0000E+02       2.9190E+00
       10        4.5000E+02       3.3630E+00
       11        4.5000E+02       3.4320E+00
       12        4.0000E+02       3.1010E+00
       13        3.5000E+02       2.7810E+00
       14        3.0000E+02       2.4170E+00
       15        2.5000E+02       2.0870E+00
       16        2.0000E+02       1.7450E+00
       17        1.5000E+02       1.3300E+00
       18        1.0000E+02       8.3300E-01
       19        5.0000E+01       1.8100E-01
       20        0.0000E+00       2.7000E-02

 ORDER OF REGRESSION = 1
 STANDARD DEVIATION  = 1.4707399E-01

 Y = 7.686061E-03 * X^ 1 -3.296364E-02
```

| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 13, DATA<br>TABLE 4·3·5 |
|---|---|---|



Test Number 13
Load On Black-White Side
Half Bridge
Excitation = 10 V GAIN = 1000

| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | TITLE: **U OF C SLIDING BLOCK CALIBRATION TEST 13, PLOT** |
| | | FIGURE No. **4·3·9** |

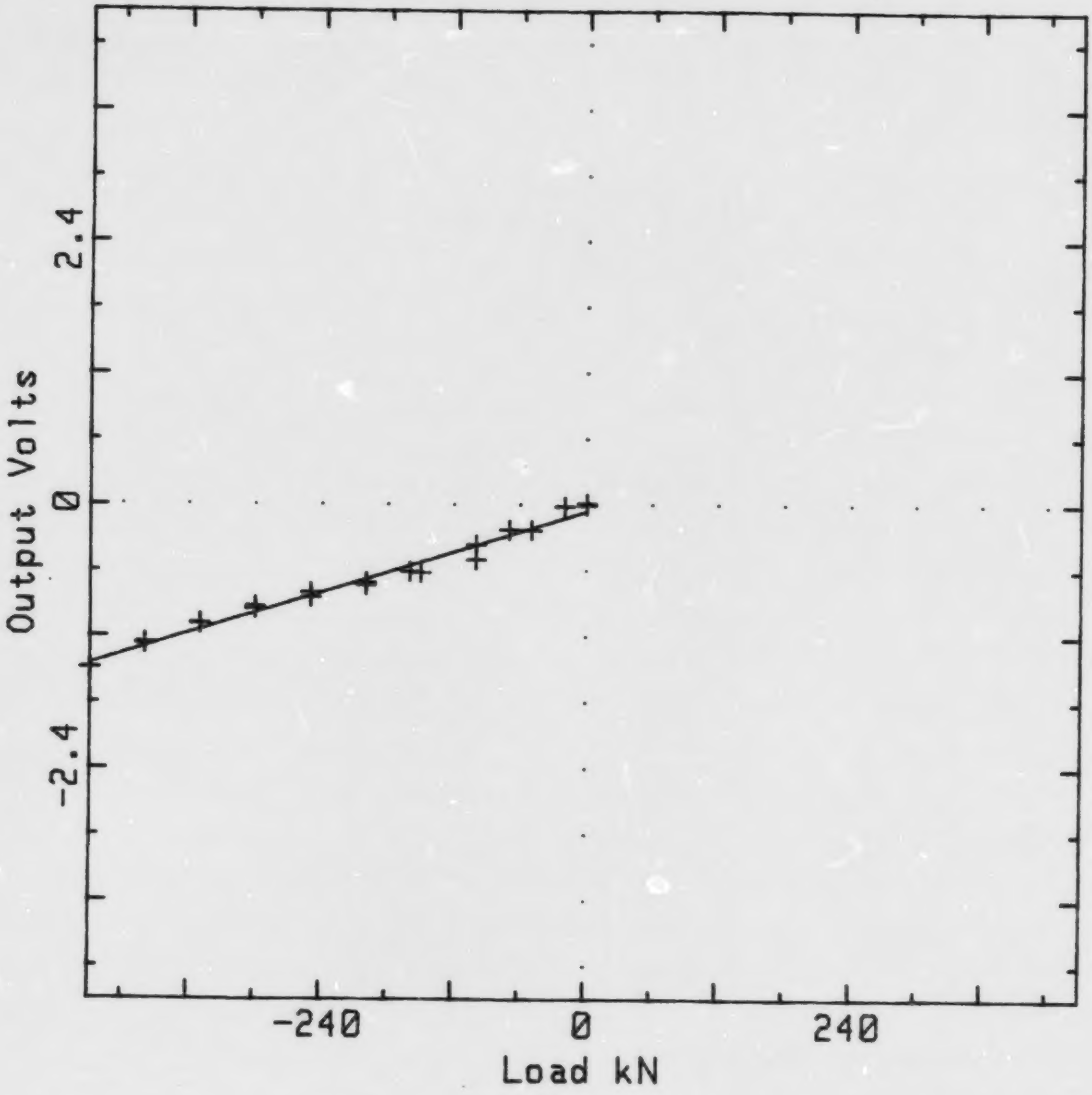
```
                    Test Number 14
                    Load On Black-White Side
                    Half Bridge
                    Sa Circuit

          X COORDINATE: Load kN
          Y COORDINATE: Output Volts

                I          X COORD.          Y COORD.          COMMENT

                1        0.0000E+00        1.0000E-03
                2       -2.0000E+01       -2.5000E-02
                3       -7.0000E+01       -2.3900E-01
                4       -1.0000E+02       -3.7500E-01
                5       -1.6000E+02       -6.2300E-01
                6       -2.0000E+02       -7.2000E-01
                7       -2.5000E+02       -8.1500E-01
                8       -3.0000E+02       -9.3900E-01
                9       -3.5000E+02       -1.0980E+00
               10       -4.0000E+02       -1.2800E+00
               11       -4.5000E+02       -1.4930E+00
               12       -4.5000E+02       -1.4960E+00
               13       -4.0000E+02       -1.2650E+00
               14       -3.5000E+02       -1.0860E+00
               15       -3.0000E+02       -9.5700E-01
               16       -2.5000E+02       -8.5000E-01
               17       -2.0000E+02       -7.3800E-01
               18       -1.5000E+02       -6.2400E-01
               19       -1.0000E+02       -5.0500E-01
               20       -5.0000E+01       -2.3500E-01
               21        0.0000E+00       -7.0000E-03

          ORDER OF REGRESSION = 1
          STANDARD DEVIATION  = 6.0694028E-02

          Y = 3.110568E-03 * X^ 1 -5.790081E-02
```

**CANADIAN**
**MARINE**
**DRILLING**
**LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 14, DATA**

**TABLE 4·3·6**

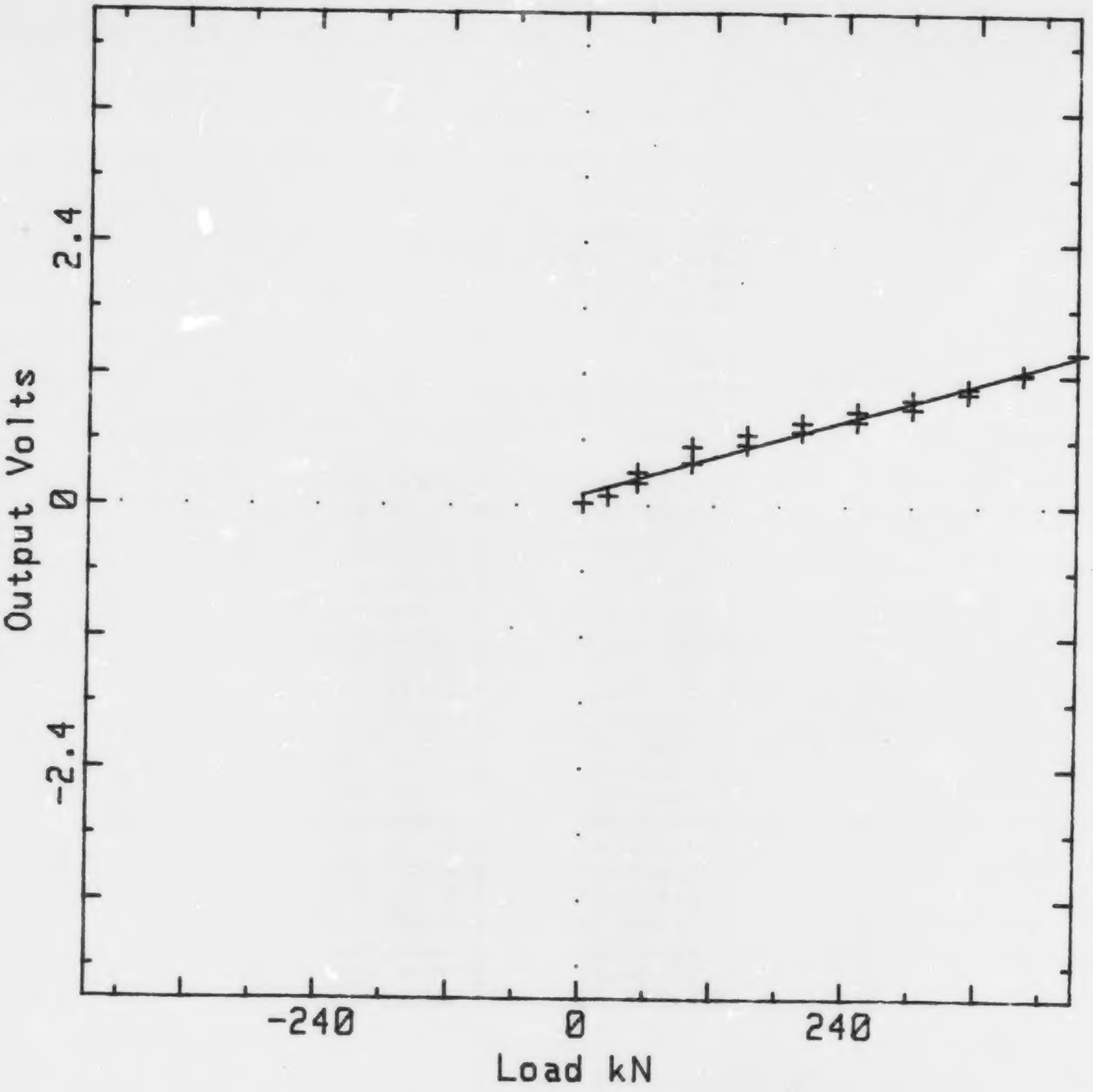


Test Number 14
Load On Black-White Side
Half Bridge
Sa Circuit

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 14, PLOT<br>FIGURE No. 4·3·10 |

```
                Test Number 15
                Load On Red-White Side
                Half Bridge
                Sa Circuit

   X COORDINATE: Load kN
   Y COORDINATE: Output Volts

         I          X COORD.          Y COORD.          COMMENT

         1        0.0000E+00        1.0000E-02
         2        2.3000E+01        8.0000E-02
         3        5.0000E+01        2.0000E-01
         4        1.0000E+02        3.8100E-01
         5        1.5000E+02        5.5200E-01
         6        2.0000E+02        6.7700E-01
         7        2.5000E+02        7.7500E-01
         8        3.0000E+02        8.9400E-01
         9        3.5000E+02        1.0360E+00
        10        4.0000E+02        1.2060E+00
        11        4.5000E+02        1.4060E+00
        12        4.5000E+02        1.4060E+00
        13        4.0000E+02        1.2160E+00
        14        3.5000E+02        1.0800E+00
        15        3.0000E+02        9.6900E-01
        16        2.5000E+02        8.6000E-01
        17        2.0000E+02        7.5300E-01
        18        1.5000E+02        6.4100E-01
        19        1.0000E+02        5.3000E-01
        20        5.0000E+01        2.9200E-01
        21        0.0000E+00        1.4000E-02

    ORDER OF REGRESSION = 1
    STANDARD DEVIATION  = 6.5966053E-02

    Y = 2.877883E-03 * X^ 1 +9.339687E-02
```

| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 15, DATA |
|---|---|---|
| | | TABLE 4·3·7 |

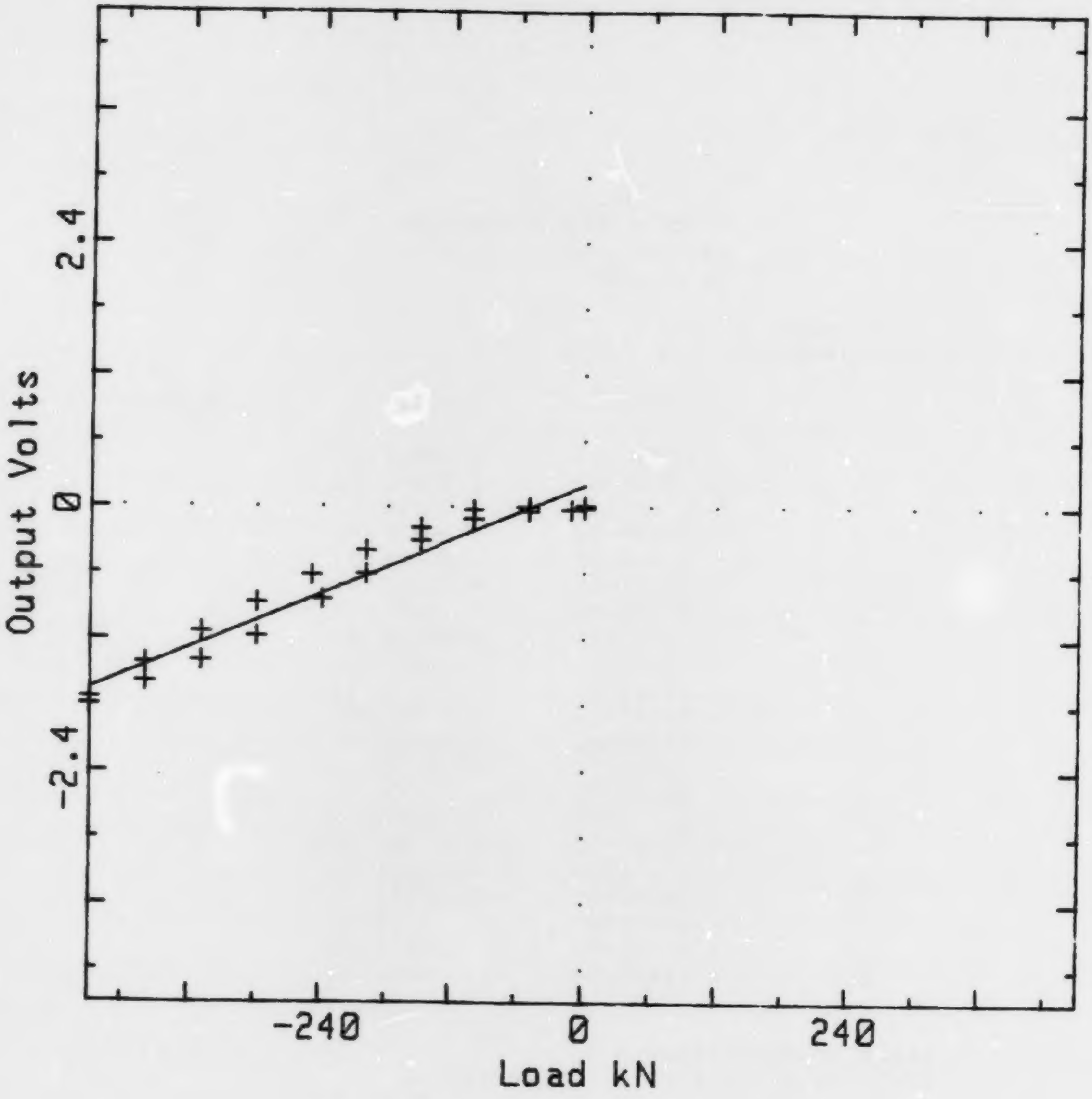


Test Number 15
Load On Red-White Side
Half Bridge
Sa Circuit

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE: U OF C SLIDING BLOCK<br>CALIBRATION TEST 15, PLOT<br>FIGURE No. 4·3·11 |

```
                    Test Number 16
                    Load On Red-White Side
                    Half Bridge
                    Sb Circuit

           X COORDINATE: Load kN
           Y COORDINATE: Output Volts

                  I         X COORD.          Y COORD.          COMMENT

                  1        0.0000E+00        0.0000E+00
                  2       -1.2000E+01       -3.5000E-02
                  3       -5.0000E+01       -1.2000E-02
                  4       -1.0000E+02       -3.4000E-02
                  5       -1.5000E+02       -1.9600E-01
                  6       -2.0000E+02       -4.0600E-01
                  7       -2.5000E+02       -6.3000E-01
                  8       -3.0000E+02       -8.8000E-01
                  9       -3.5000E+02       -1.1450E+00
                 10       -4.0000E+02       -1.4230E+00
                 11       -4.5000E+02       -1.7400E+00
                 12       -4.5050E+02       -1.8000E+00
                 13       -4.0000E+02       -1.5930E+00
                 14       -3.5000E+02       -1.4010E+00
                 15       -3.0000E+02       -1.1800E+00
                 16       -2.4000E+02       -8.4100E-01
                 17       -2.0000E+02       -6.1000E-01
                 18       -1.5000E+02       -3.0800E-01
                 19       -1.0000E+02       -1.1300E-01
                 20       -5.0000E+01       -4.2000E-02
                 21        0.0000E+00       -1.8000E-02

            ORDER OF REGRESSION = 1
            STANDARD DEVIATION  = 1.5320704E-01

            Y = 4.120973E-03 * X^ 1 +1.975086E-01
```

| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 16, DATA<br>TABLE 4·3·8 |
|---|---|---|



Test Number 16
Load On Red-White Side
Half Bridge
Sb Circuit

CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE
PROPELLER INTERACTION
PARAMETERS

TITLE: U OF C SLIDING BLOCK
CALIBRATION TEST 16, PLOT

FIGURE No. 4·3·12

Test Numbers 11B 11C 12A 12B
Full Bridge
Excitation = 10 V     Gain = 1000

X COORDINATE: Load kN
Y COORDINATE: Output Volts

| I | X COORD. | Y COORD. | COMMENT |
|---|---|---|---|
| 1 | 0.0000E+00 | -1.5000E-02 | |
| 2 | -1.2800E+01 | -1.2700E-01 | |
| 3 | -5.0000E+01 | -3.1800E-01 | |
| 4 | -1.0000E+02 | -7.1800E-01 | |
| 5 | -1.5000E+02 | -1.0940E+00 | |
| 6 | -2.0000E+02 | -1.3400E+00 | |
| 7 | -2.5000E+02 | -1.6400E+00 | |
| 8 | -3.0000E+02 | -2.0290E+00 | |
| 9 | -3.5000E+02 | -2.4790E+00 | |
| 10 | -4.0000E+02 | -2.9700E+00 | |
| 11 | -4.5000E+02 | -3.5400E+00 | |
| 12 | -4.5200E+02 | -3.6630E+00 | |
| 13 | -4.0000E+02 | -3.1790E+00 | |
| 14 | -3.5000E+02 | -2.8020E+00 | |
| 15 | -3.0000E+02 | -2.4210E+00 | |
| 16 | -2.5000E+02 | -2.0890E+00 | |
| 17 | -2.0000E+02 | -1.7320E+00 | |
| 18 | -1.5000E+02 | -1.3150E+00 | |
| 19 | -1.0000E+02 | -9.1500E-01 | |
| 20 | -5.0000E+01 | -5.5000E-01 | |
| 21 | 2.2000E-01 | -2.1800E-01 | |
| 22 | 0.0000E+00 | -2.2200E-01 | |
| 23 | -9.5000E+00 | -2.6000E-01 | |
| 24 | -5.0000E+01 | -4.0800E-01 | |
| 25 | -1.0000E+02 | -7.2300E-01 | |
| 26 | -1.5000E+02 | -1.2920E+00 | |
| 27 | -2.0000E+02 | -1.7130E+00 | |
| 28 | -2.5000E+02 | -2.1000E+00 | |
| 29 | -3.0000E+02 | -2.5430E+00 | |
| 30 | -3.5000E+02 | -3.0190E+00 | |
| 31 | -4.0000E+02 | -3.5300E+00 | |
| 32 | -4.5000E+02 | -4.1100E+00 | |
| 33 | -4.5160E+02 | -4.1890E+00 | |
| 34 | -4.0000E+02 | -3.7430E+00 | |
| 35 | -3.5000E+02 | -3.3630E+00 | |
| 36 | -3.0000E+02 | -2.9630E+00 | |
| 37 | -2.5000E+02 | -2.5520E+00 | |
| 38 | -2.0000E+02 | -2.0700E+00 | |
| 39 | -1.5000E+02 | -1.5320E+00 | |
| 40 | -1.0000E+02 | -9.6000E-01 | |
| 41 | -5.0000E+01 | -5.4400E-01 | |
| 42 | 0.0000E+00 | -2.5800E-01 | |
| 43 | 0.0000E+00 | -2.4900E-01 | |
| 44 | 1.6000E+01 | -1.6300E-01 | |
| 45 | 5.0000E+01 | -2.0000E-02 | |
| 46 | 1.0000E+02 | 5.3000E-01 | |
| 47 | 1.5000E+02 | 1.1400E+00 | |
| 48 | 2.0000E+02 | 1.6000E+00 | |
| 49 | 2.5000E+02 | 1.9700E+00 | |
| 50 | 3.0000E+02 | 2.4030E+00 | |
| 51 | 3.5000E+02 | 2.8800E+00 | |
| 52 | 4.0000E+02 | 3.4000E+00 | |
| 53 | 4.5000E+02 | 3.9900E+00 | |
| 54 | 4.5000E+02 | 4.0459E+00 | |
| 55 | 4.0000E+02 | 3.5390E+00 | |

**CANADIAN MARINE DRILLING LIMITED**

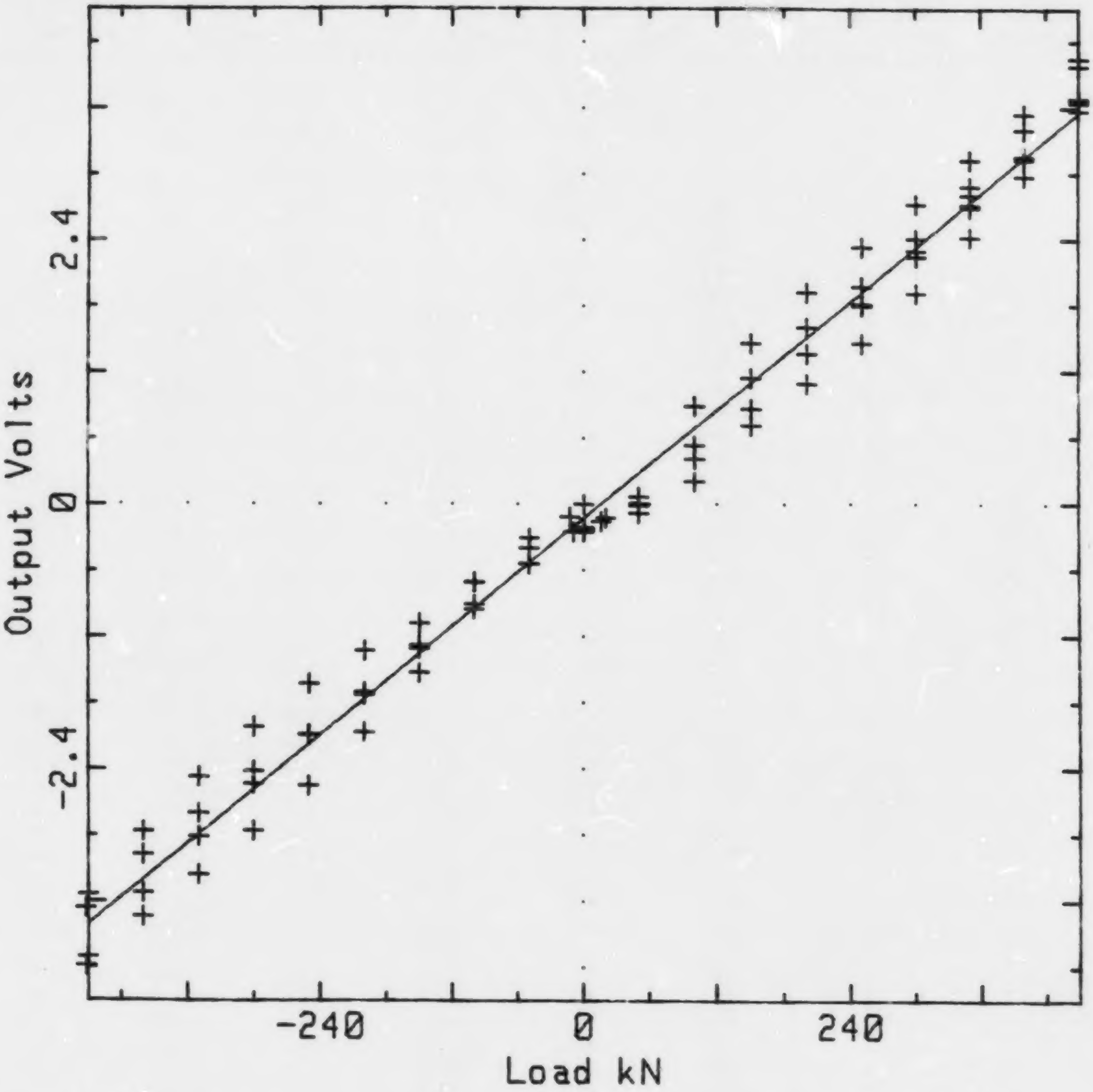
**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 11B, 11C, 12A, 12B, DATA**

**TABLE 4·3·9 A**

```
56         3.5000E+02      3.1170E+00
57         3.0000E+02      2.7090E+00
58         2.5000E+02      2.3190E+00
59         2.0000E+02      1.9090E+00
60         1.5000E+02      1.4500E+00
61         1.0000E+02      8.7900E-01
62         5.0000E+01      5.6000E-02
63         0.0000E+00     -2.4700E-01
64         0.0000E+00     -2.4200E-01
65         0.0000E+00     -2.4700E-01
66         2.0100E+01     -1.3300E-01
67         5.0000E+01     -8.9000E-02
68         1.0000E+02      2.0200E-01
69         1.5000E+02      7.0800E-01
70         2.0000E+02      1.0880E+00
71         2.5000E+02      1.4560E+00
72         3.0000E+02      1.9100E+00
73         3.5000E+02      2.4180E+00
74         4.0000E+02      2.9750E+00
75         4.5000E+02      3.5760E+00
76         4.5030E+02      3.6440E+00
77         4.0000E+02      3.1210E+00
78         3.5000E+02      2.6800E+00
79         3.0000E+02      2.2330E+00
80         2.5000E+02      1.7670E+00
81         2.5000E+02      1.7910E+00
82         3.0000E+02      2.2890E+00
83         3.5000E+02      2.7090E+00
84         4.0000E+02      3.1540E+00
85         4.5000E+02      3.6730E+00
86         4.5000E+02      3.6850E+00
87         4.0000E+02      3.1480E+00
88         3.5000E+02      2.7950E+00
89         3.0000E+02      2.2370E+00
90         2.5000E+02      1.8040E+00
91         2.0000E+02      1.3520E+00
92         1.5000E+02      8.5300E-01
93         1.0000E+02      4.0000E-01
94         5.0000E+01     -3.0000E-03
95         0.0000E+00     -2.2700E-01

ORDER OF REGRESSION = 1
STANDARD DEVIATION  = 2.5369758E-01

Y = 8.193797E-03 * X^ 1 -1.265277E-01
```

| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 11B, 11C, 12A, 12B, DATA |
|---|---|---|
| | | TABLE 4·3·9 B |



Test Numbers 11B 11C 12A 12B
Full Bridge
Excitation = 10 V Gain = 1000

**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

TITLE: U OF C SLIDING BLOCK CALIBRATION TEST 11B, 11C, 12A, 12B, PLOT

FIGURE No. 4·3·13

FRICTION IS NOT INCLUDED IN THESE CALCULATIONS    VERSION 1.01

| LOAD POINT NUMBER | LOAD CASE NUMBER | IN PLANE FORCE kN/kN | OUT PLANE FORCE kN/kN | IN PLANE BENDING kNm/kN | OUT PLANE BENDING kNm/kN | SLIDING BLK FORCE kN/kN | SERVO OIL PRESSURE kPa/kN |
|---|---|---|---|---|---|---|---|
| 1 | 1 | .205 | -.979 | .188 | -.898 | -2.388 | .139 |
| 2 | 1 | .205 | -.979 | .197 | -.941 | -1.877 | .109 |
| 3 | 1 | .205 | -.979 | .204 | -.974 | -1.351 | .079 |
| 4 | 1 | .205 | -.979 | .208 | -.996 | -.815 | .047 |
| 5 | 1 | .205 | -.979 | .211 | -1.008 | 0.000 | 0.000 |
| 6 | 1 | .205 | -.979 | .204 | -.974 | 1.351 | -.079 |
| 7 | 1 | .205 | -.979 | .188 | -.898 | 2.388 | -.139 |
| 8 | 1 | .205 | -.979 | .158 | -.753 | -2.540 | .148 |
| 9 | 1 | .205 | -.979 | .169 | -.807 | -2.004 | .117 |
| 10 | 1 | .205 | -.979 | .177 | -.848 | -1.446 | .084 |
| 11 | 1 | .205 | -.979 | .183 | -.875 | -.874 | .051 |
| 12 | 1 | .205 | -.979 | .187 | -.891 | 0.000 | 0.000 |
| 13 | 1 | .205 | -.979 | .177 | -.848 | 1.446 | -.084 |
| 14 | 1 | .205 | -.979 | .158 | -.753 | 2.540 | -.148 |
| 15 | 1 | .205 | -.979 | .125 | -.598 | -2.448 | .143 |
| 16 | 1 | .205 | -.979 | .137 | -.655 | -1.936 | .113 |
| 17 | 1 | .205 | -.979 | .146 | -.698 | -1.401 | .082 |
| 18 | 1 | .205 | -.979 | .152 | -.727 | -.848 | .049 |
| 19 | 1 | .205 | -.979 | .156 | -.744 | 0.000 | 0.000 |
| 20 | 1 | .205 | -.979 | .146 | -.698 | 1.401 | -.082 |
| 21 | 1 | .205 | -.979 | .125 | -.598 | 2.448 | -.143 |
| 22 | 1 | .205 | -.979 | .097 | -.462 | -2.197 | .128 |
| 23 | 1 | .205 | -.979 | .108 | -.514 | -1.740 | .101 |
| 24 | 1 | .205 | -.979 | .116 | -.555 | -1.259 | .073 |
| 25 | 1 | .205 | -.979 | .122 | -.582 | -.762 | .044 |
| 26 | 1 | .205 | -.979 | .125 | -.597 | 0.000 | 0.000 |
| 27 | 1 | .205 | -.979 | .116 | -.555 | 1.259 | -.073 |
| 28 | 1 | .205 | -.979 | .097 | -.462 | 2.197 | -.128 |
| 29 | 1 | .205 | -.979 | .070 | -.332 | -1.891 | .110 |
| 30 | 1 | .205 | -.979 | .079 | -.378 | -1.498 | .087 |
| 31 | 1 | .205 | -.979 | .087 | -.413 | -1.085 | .063 |
| 32 | 1 | .205 | -.979 | .091 | -.437 | -.657 | .038 |
| 33 | 1 | .205 | -.979 | .087 | -.413 | 1.085 | -.063 |
| 34 | 1 | .205 | -.979 | .070 | -.332 | 1.891 | -.110 |
| 35 | 1 | .205 | -.979 | .043 | -.207 | -1.547 | .090 |
| 36 | 1 | .205 | -.979 | .064 | -.303 | 0.000 | 0.000 |
| 1 | 2 | .404 | -.915 | .370 | -.839 | -2.348 | .137 |
| 2 | 2 | .404 | -.915 | .388 | -.879 | -1.845 | .107 |
| 3 | 2 | .404 | -.915 | .402 | -.910 | -1.328 | .077 |
| 4 | 2 | .404 | -.915 | .411 | -.931 | -.801 | .047 |
| 5 | 2 | .404 | -.915 | .416 | -.942 | 0.000 | 0.000 |
| 6 | 2 | .404 | -.915 | .402 | -.910 | 1.328 | -.077 |
| 7 | 2 | .404 | -.915 | .370 | -.839 | 2.348 | -.137 |
| 8 | 2 | .404 | -.915 | .311 | -.703 | -2.484 | .145 |
| 9 | 2 | .404 | -.915 | .333 | -.754 | -1.960 | .114 |
| 10 | 2 | .404 | -.915 | .350 | -.792 | -1.415 | .082 |
| 11 | 2 | .404 | -.915 | .361 | -.818 | -.855 | .050 |
| 12 | 2 | .404 | -.915 | .368 | -.832 | 0.000 | 0.000 |
| 13 | 2 | .404 | -.915 | .350 | -.792 | 1.415 | -.082 |
| 14 | 2 | .404 | -.915 | .311 | -.703 | 2.484 | -.145 |

TITLE: CALCULATED RESULTANT FORCES VS LOAD FOR ALL LOAD POINTS AND CASES

TABLE 4·4·1

FRICTION IS NOT INCLUDED IN THESE CALCULATIONS     VERSION 1.01

| LOAD POINT NUMBER | LOAD CASE NUMBER | IN PLANE FORCE kN/kN | OUT PLANE FORCE kN/kN | IN PLANE BENDING kNm/kN | OUT PLANE BENDING kNm/kN | SLIDING BLK FORCE kN/kN | SERVO OIL PRESSURE kPa/kN |
|---|---|---|---|---|---|---|---|
| 15 | 2 | .404 | -.915 | .247 | -.559 | -2.378 | .139 |
| 16 | 2 | .404 | -.915 | .270 | -.612 | -1.881 | .110 |
| 17 | 2 | .404 | -.915 | .288 | -.653 | -1.361 | .079 |
| 18 | 2 | .404 | -.915 | .300 | -.680 | -.823 | .048 |
| 19 | 2 | .404 | -.915 | .307 | -.695 | 0.000 | 0.000 |
| 20 | 2 | .404 | -.915 | .288 | -.653 | 1.361 | -.079 |
| 21 | 2 | .404 | -.915 | .247 | -.559 | 2.378 | -.139 |
| 22 | 2 | .404 | -.915 | .191 | -.432 | -2.117 | .123 |
| 23 | 2 | .404 | -.915 | .212 | -.481 | -1.676 | .098 |
| 24 | 2 | .404 | -.915 | .229 | -.518 | -1.214 | .071 |
| 25 | 2 | .404 | -.915 | .240 | -.544 | -.735 | .043 |
| 26 | 2 | .404 | -.915 | .246 | -.558 | 0.000 | 0.000 |
| 27 | 2 | .404 | -.915 | .229 | -.518 | 1.214 | -.071 |
| 28 | 2 | .404 | -.915 | .191 | -.432 | 2.117 | -.123 |
| 29 | 2 | .404 | -.915 | .137 | -.310 | -1.802 | .105 |
| 30 | 2 | .404 | -.915 | .156 | -.353 | -1.428 | .083 |
| 31 | 2 | .404 | -.915 | .171 | -.386 | -1.034 | .060 |
| 32 | 2 | .404 | -.915 | .180 | -.408 | -.626 | .036 |
| 33 | 2 | .404 | -.915 | .171 | -.386 | 1.034 | -.060 |
| 34 | 2 | .404 | -.915 | .137 | -.310 | 1.802 | -.105 |
| 35 | 2 | .404 | -.915 | .085 | -.193 | -1.453 | .085 |
| 36 | 2 | .404 | -.915 | .125 | -.284 | 0.000 | 0.000 |
| 1 | 3 | -.003 | -1.000 | -.003 | -.917 | -2.324 | .135 |
| 2 | 3 | -.003 | -1.000 | -.003 | -.961 | -1.827 | .106 |
| 3 | 3 | -.003 | -1.000 | -.003 | -.995 | -1.315 | .077 |
| 4 | 3 | -.003 | -1.000 | -.003 | -1.017 | -.793 | .046 |
| 5 | 3 | -.003 | -1.000 | -.003 | -1.030 | 0.000 | 0.000 |
| 6 | 3 | -.003 | -1.000 | -.003 | -.995 | 1.315 | -.077 |
| 7 | 3 | -.003 | -1.000 | -.003 | -.917 | 2.324 | -.135 |
| 8 | 3 | -.003 | -1.000 | -.002 | -.769 | -2.485 | .145 |
| 9 | 3 | -.003 | -1.000 | -.002 | -.824 | -1.960 | .114 |
| 10 | 3 | -.003 | -1.000 | -.003 | -.866 | -1.415 | .082 |
| 11 | 3 | -.003 | -1.000 | -.003 | -.894 | -.855 | .050 |
| 12 | 3 | -.003 | -1.000 | -.003 | -.910 | 0.000 | 0.000 |
| 13 | 3 | -.003 | -1.000 | -.003 | -.866 | 1.415 | -.082 |
| 14 | 3 | -.003 | -1.000 | -.002 | -.769 | 2.485 | -.145 |
| 15 | 3 | -.003 | -1.000 | -.002 | -.611 | -2.411 | .140 |
| 16 | 3 | -.003 | -1.000 | -.002 | -.669 | -1.907 | .111 |
| 17 | 3 | -.003 | -1.000 | -.002 | -.713 | -1.379 | .080 |
| 18 | 3 | -.003 | -1.000 | -.002 | -.743 | -.835 | .049 |
| 19 | 3 | -.003 | -1.000 | -.002 | -.760 | 0.000 | 0.000 |
| 20 | 3 | -.003 | -1.000 | -.002 | -.713 | 1.379 | -.080 |
| 21 | 3 | -.003 | -1.000 | -.002 | -.611 | 2.411 | -.140 |
| 22 | 3 | -.003 | -1.000 | -.001 | -.472 | -2.181 | .127 |
| 23 | 3 | -.003 | -1.000 | -.002 | -.526 | -1.727 | .101 |
| 24 | 3 | -.003 | -1.000 | -.002 | -.567 | -1.250 | .073 |
| 25 | 3 | -.003 | -1.000 | -.002 | -.594 | -.757 | .044 |
| 26 | 3 | -.003 | -1.000 | -.002 | -.610 | 0.000 | 0.000 |
| 27 | 3 | -.003 | -1.000 | -.002 | -.567 | 1.250 | -.073 |
| 28 | 3 | -.003 | -1.000 | -.001 | -.472 | 2.181 | -.127 |

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PARAMETERS

TITLE: CALCULATED RESULTANT FORCES VS LOAD FOR ALL LOAD POINTS AND CASES

TABLE 4·4·1 (CONT.)

FRICTION IS NOT INCLUDED IN THESE CALCULATIONS    VERSION 1.01

| LOAD POINT NUMBER | LOAD CASE NUMBER | IN PLANE FORCE kN/kN | OUT PLANE FORCE kN/kN | IN PLANE BENDING kNm/kN | OUT PLANE BENDING kNm/kN | SLIDING BLK FORCE kN/kN | SERVO OIL PRESSURE kPa/kN |
|---|---|---|---|---|---|---|---|
| 29 | 3 | -.003 | -1.000 | -.001 | -.339 | -1.896 | .110 |
| 30 | 3 | -.003 | -1.000 | -.001 | -.386 | -1.502 | .088 |
| 31 | 3 | -.003 | -1.000 | -.001 | -.422 | -1.088 | .063 |
| 32 | 3 | -.003 | -1.000 | -.001 | -.446 | -.659 | .038 |
| 33 | 3 | -.003 | -1.000 | -.001 | -.422 | 1.088 | -.063 |
| 34 | 3 | -.003 | -1.000 | -.001 | -.339 | 1.896 | -.110 |
| 35 | 3 | -.003 | -1.000 | -.001 | -.211 | -1.572 | .092 |
| 36 | 3 | -.003 | -1.000 | -.001 | -.310 | 0.000 | 0.000 |
| 1 | 4 | .200 | -.957 | .184 | -.878 | -2.336 | .136 |
| 2 | 4 | .200 | -.957 | .193 | -.920 | -1.836 | .107 |
| 3 | 4 | .200 | -.957 | .199 | -.952 | -1.321 | .077 |
| 4 | 4 | .200 | -.957 | .204 | -.974 | -.797 | .046 |
| 5 | 4 | .200 | -.957 | .206 | -.986 | 0.000 | 0.000 |
| 6 | 4 | .200 | -.957 | .199 | -.952 | 1.321 | -.077 |
| 7 | 4 | .200 | -.957 | .184 | -.878 | 2.336 | -.136 |
| 8 | 4 | .200 | -.957 | .154 | -.736 | -2.484 | .145 |
| 9 | 4 | .200 | -.957 | .165 | -.789 | -1.960 | .114 |
| 10 | 4 | .200 | -.957 | .174 | -.829 | -1.415 | .082 |
| 11 | 4 | .200 | -.957 | .179 | -.856 | -.855 | .050 |
| 12 | 4 | .200 | -.957 | .182 | -.871 | 0.000 | 0.000 |
| 13 | 4 | .200 | -.957 | .174 | -.829 | 1.415 | -.082 |
| 14 | 4 | .200 | -.957 | .154 | -.736 | 2.484 | -.145 |
| 15 | 4 | .200 | -.957 | .122 | -.585 | -2.394 | .139 |
| 16 | 4 | .200 | -.957 | .134 | -.641 | -1.894 | .110 |
| 17 | 4 | .200 | -.957 | .143 | -.683 | -1.370 | .080 |
| 18 | 4 | .200 | -.957 | .149 | -.711 | -.829 | .048 |
| 19 | 4 | .200 | -.957 | .152 | -.728 | 0.000 | 0.000 |
| 20 | 4 | .200 | -.957 | .143 | -.683 | 1.370 | -.080 |
| 21 | 4 | .200 | -.957 | .122 | -.585 | 2.394 | -.139 |
| 22 | 4 | .200 | -.957 | .095 | -.452 | -2.149 | .125 |
| 23 | 4 | .200 | -.957 | .105 | -.503 | -1.702 | .099 |
| 24 | 4 | .200 | -.957 | .114 | -.543 | -1.232 | .072 |
| 25 | 4 | .200 | -.957 | .119 | -.569 | -.746 | .043 |
| 26 | 4 | .200 | -.957 | .122 | -.584 | 0.000 | 0.000 |
| 27 | 4 | .200 | -.957 | .114 | -.543 | 1.232 | -.072 |
| 28 | 4 | .200 | -.957 | .095 | -.452 | 2.149 | -.125 |
| 29 | 4 | .200 | -.957 | .068 | -.325 | -1.849 | .108 |
| 30 | 4 | .200 | -.957 | .077 | -.370 | -1.465 | .085 |
| 31 | 4 | .200 | -.957 | .085 | -.404 | -1.061 | .062 |
| 32 | 4 | .200 | -.957 | .089 | -.427 | -.642 | .037 |
| 33 | 4 | .200 | -.957 | .085 | -.404 | 1.061 | -.062 |
| 34 | 4 | .200 | -.957 | .068 | -.325 | 1.849 | -.108 |
| 35 | 4 | .200 | -.957 | .042 | -.202 | -1.513 | .088 |
| 36 | 4 | .200 | -.957 | .062 | -.297 | 0.000 | 0.000 |
| 1 | 5 | .200 | -.957 | .184 | -.878 | -2.336 | .136 |
| 2 | 5 | .200 | -.957 | .193 | -.920 | -1.836 | .107 |
| 3 | 5 | .200 | -.957 | .199 | -.952 | -1.321 | .077 |
| 4 | 5 | .200 | -.957 | .204 | -.974 | -.797 | .046 |
| 5 | 5 | .200 | -.957 | .206 | -.986 | 0.000 | 0.000 |
| 6 | 5 | .200 | -.957 | .199 | -.952 | 1.321 | -.077 |

TITLE: CALCULATED RESULTANT FORCES VS LOAD FOR ALL LOAD POINTS AND CASES

TABLE 4·4·1 (CONT.)

FRICTION IS NOT INCLUDED IN THESE CALCULATIONS    VERSION 1.01

| LOAD POINT NUMBER | LOAD CASE NUMBER | IN PLANE FORCE kN/kN | OUT PLANE FORCE kN/kN | IN PLANE BENDING kNm/kN | OUT PLANE BENDING kNm/kN | SLIDING BLK FORCE kN/kN | SERVO OIL PRESSURE kPa/kN |
|---|---|---|---|---|---|---|---|
| 7 | 5 | .200 | -.957 | .184 | -.870 | 2.336 | -.136 |
| 8 | 5 | .200 | -.957 | .154 | -.736 | -2.484 | .145 |
| 9 | 5 | .200 | -.957 | .165 | -.789 | -1.960 | .114 |
| 10 | 5 | .200 | -.957 | .174 | -.829 | -1.415 | .082 |
| 11 | 5 | .200 | -.957 | .179 | -.856 | -.855 | .050 |
| 12 | 5 | .200 | -.957 | .182 | -.871 | 0.000 | 0.000 |
| 13 | 5 | .200 | -.957 | .174 | -.829 | 1.415 | -.082 |
| 14 | 5 | .200 | -.957 | .154 | -.736 | 2.484 | -.145 |
| 15 | 5 | .200 | -.957 | .122 | -.585 | -2.394 | .139 |
| 16 | 5 | .200 | -.957 | .134 | -.641 | -1.894 | .110 |
| 17 | 5 | .200 | -.957 | .143 | -.683 | -1.370 | .080 |
| 18 | 5 | .200 | -.957 | .149 | -.711 | -.829 | .048 |
| 19 | 5 | .200 | -.957 | .152 | -.728 | 0.000 | 0.000 |
| 20 | 5 | .200 | -.957 | .143 | -.683 | 1.370 | -.080 |
| 21 | 5 | .200 | -.957 | .122 | -.585 | 2.394 | -.139 |
| 22 | 5 | .200 | -.957 | .095 | -.452 | -2.149 | .125 |
| 23 | 5 | .200 | -.957 | .105 | -.503 | -1.702 | .099 |
| 24 | 5 | .200 | -.957 | .114 | -.543 | -1.232 | .072 |
| 25 | 5 | .200 | -.957 | .119 | -.569 | -.746 | .043 |
| 26 | 5 | .200 | -.957 | .122 | -.584 | 0.000 | 0.000 |
| 27 | 5 | .200 | -.957 | .114 | -.543 | 1.232 | -.072 |
| 28 | 5 | .200 | -.957 | .095 | -.452 | 2.149 | -.125 |
| 29 | 5 | .200 | -.957 | .068 | -.325 | -1.849 | .108 |
| 30 | 5 | .200 | -.957 | .077 | -.370 | -1.465 | .085 |
| 31 | 5 | .200 | -.957 | .085 | -.404 | -1.061 | .062 |
| 32 | 5 | .200 | -.957 | .089 | -.427 | -.642 | .037 |
| 33 | 5 | .200 | -.957 | .085 | -.404 | 1.061 | -.062 |
| 34 | 5 | .200 | -.957 | .068 | -.325 | 1.849 | -.108 |
| 35 | 5 | .200 | -.957 | .042 | -.202 | -1.513 | .088 |
| 36 | 5 | .200 | -.957 | .062 | -.297 | 0.000 | 0.000 |
| 37 | 6 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 38 | 7 | .955 | .296 | .703 | .218 | -.264 | .015 |

CANMAR

**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE: CALCULATED RESULTANT FORCES VS LOAD FOR ALL LOAD POINTS AND CASES**

**TABLE 4·4·1 (CONT.)**

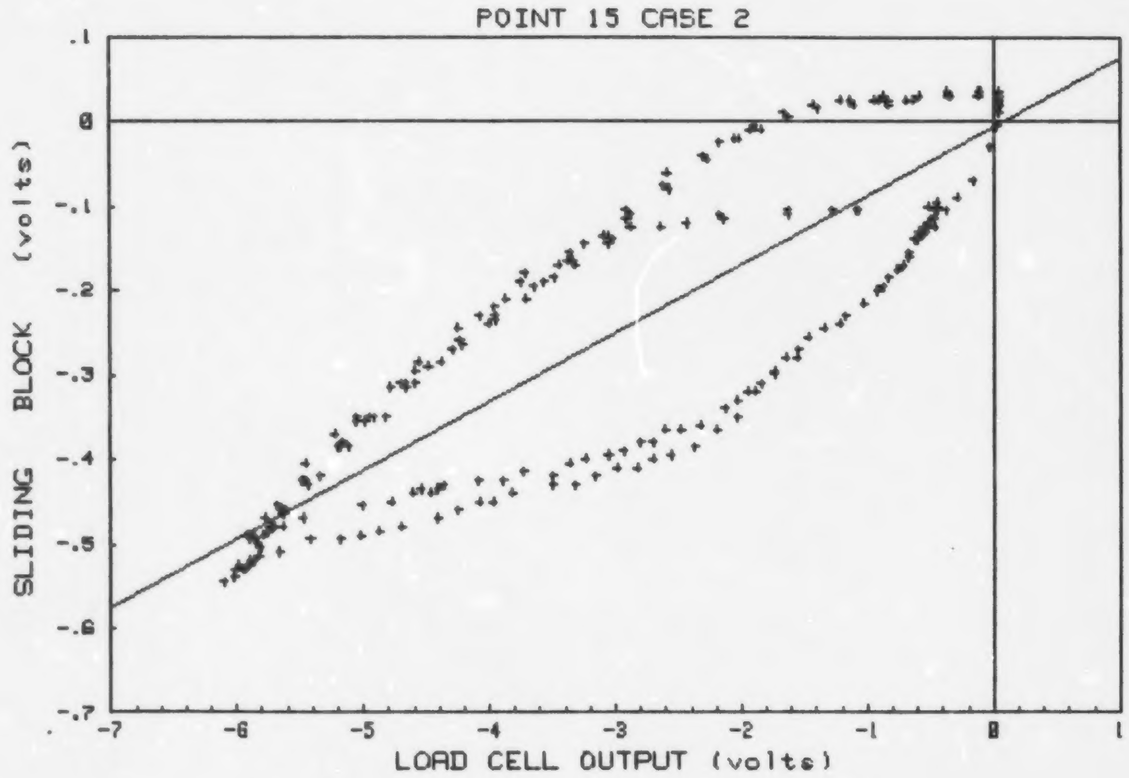
points and cases specified are given in Table 4.4.1. It should be noted that these are predicted values, ie. neglecting friction and assuming the load is applied at the exact angle and location specified.

A sample of the output calibration signal from the sliding block is given in Figure 4.4.1. This figure shows the individual points recorded during a single static calibration. The same data points are reported in Figure 4.4.2, in which the individual points are joined by straight lines in the order in which they were recorded. This calibration data is the same static calibration point and case combination (PT15-C2), presented in the static calibration discussion in Section 3.

The hysteresis evident in the sliding block signal is clearly visible in Figure 4.4.2. This hysteresis may be due to friction in the blade carrier bearings. This same hysteresis in the sliding block signal was noted during the ship testing, and is analyzed in detail in the final report.

The calibration data recorded on the John Wurmlinger requires further comparison to the sliding block calibration data measured in Calgary. This is because the calibration in Calgary was performed with the load spread evenly over the whole face of the sliding block; while in operational mode, the whole face of the sliding block may not be evenly supported.

A sample of the dynamic calibration of the sliding block is given in Figure 3.3.8. In comparing the force on the sliding block to the calculated spindle torque, it is necessary to know the propeller pitch. This is because the length of the lever arm resisting torsion varies with pitch angle. In addition to this, at some pitch angles, the end of the sliding block protrudes out of the end of the hub carrier slide, changing the load distribution on the face of the sliding block.



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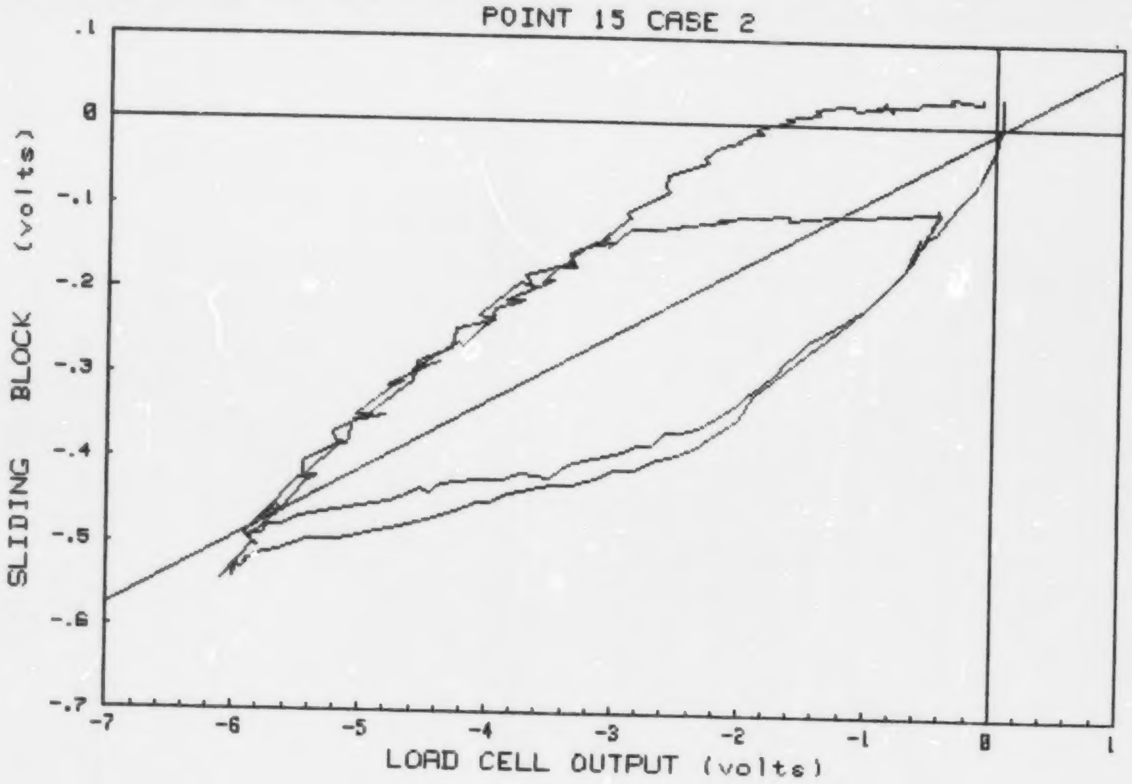
**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE: STATIC CALIBRATION, WURMLINGER SLIDING BLOCK VS LOAD CELL OUTPUTS PT15-C2**

**FIGURE No. 4.4.1**



| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | **TITLE: STATIC CALIBRATION, WURMLINGER SLIDING BLOCK VS LOAD CELL OUTPUTS PT15-C2 (LINE PLOT)**<br>**FIGURE No. 4.4.2** |

# 5. ON BOARD DATA ANALYSIS CAPABILITY

## 5.1 Introduction

A major objective of the project was to provide a high level of onboard data inspection and analysis capability. The 1983 test data, although limited in scope, provided an excellent resource for indicating which features should be provided for the current 1984 program. Other full scale ship testing programs performed by Canmar personnel also provided useful experience for the project team.

During the June 1983 full scale data collection period, data was stored on analogue tape and analysed after the tests in the laboratories of Technical Research Centre of Finland, Ship Laboratories. The onboard capability was limited to viewing the unprocessed analogue signals by means of an oscilloscope or high speed multi-channel strip chart recorder. A device for performing Fourier Transforms of the data was also available (a Hewlett Packard 3582A Dual Channel Spectrum Analyzer) to allow spectral analysis of incoming or stored data.

The justification for providing an onboard analysis and data inspection capability was that it would provide the on-site test team with feedback on the performance of the instrumentation and the equipment. Consequently, corrective action or changes in test plan could be made during the data collection phase when they could maximize the effect on the project outcome. The ability to view the collected data in either raw voltage or in engineering units was required. Furthermore, it was desirable that the influence coefficient [A] matrix be incorporated in the system, to process the blade data which would provide estimates of ice interaction force, etc. The ability to digitally filter the blade data to remove high frequency signal components was also required as was the ability to perform Fast Fourier Transforms of the data. Lastly, the ability to display the shaft movement data in an X-Y plot format was thought to be an advantage.

For the 1984 field program, one Hewlett Packard HP 9836 desk top computer acquired and stored the event data on 5 1/4" floppy disks and a second HP 9836 performed the inspection and analysis of the data files. All analysis programs were written in HP Extended Basic version 2.1 and the analysis program called "ANALYZE" had approximately 1500 lines of code.

## 5.2 Details Of The Program "ANALYZE"

A listing of the "ANALYZE" program is given in Appendix G. The "ANALYZE" program has since been updated, we shall however, describe the features available during the tests and illustrate them by means of representative data plots.

In Figure 5.2.1 are listed the eighteen channels of data that were acquired during the test program. For some of the earlier events the starboard engine fuel rack signal was not collected. Channels 19 to 35 contain the results of calculations performed on other channels of data.

Figure 5.2.2 shows the complete 7,000 readings for one event (Test 62) for one blade strain gauge signal. In order to view the details of the wave form more clearly, a 0.4 s segment of the data is shown in Figure 5.2.3, where the vertical scale has been optimized for clarity. The scaling and display features were available for any of the 35 channels of acquired or calculated data.

By use of the influence coefficient matrix [A], the six (or less) strain gauge signals, were used to provide time histories of blade force, bending moment and spindle torque. The in-plane bending moment was not calculated for the reason discussed in Section 3.1 A one second segment of each force, moment and torque, are shown in Figures 5.2.4 to 5.2.6. The radial and circumferential location of the load applied to the blade are shown in Figures 5.2.7 and 5.2.8 respectively. For Figure 5.2.7, the zero location refers to the root of the blade and in Figure 5.2.8 zero refers to the center line of the blade with positive being towards the leading edge and negative towards the trailing edge. As these quantities are calculated using equations 3.1.5 and 3.1.6, if F approaches zero, due to blade vibration or small electrical offsets, the coordinates of the load location point can be erroneous.

The blade force, bending moment, and spindle torque data shown in Figures 5.2.3 to 5.2.8 are based on raw data from the strain gauges. The signals contain components from the normal hydrodynamic forces on the blade as well as the perturbations caused by ice propeller interaction. In an attempt to remove the normal hydrodynamic component from the data, and henceforth view the ice related part of the signal, the following method was used and is

## CHANNEL DESCRIPTIONS

### ACQUIRED CHANNELS

| | | |
|---|---|---|
| 1 | CENTRE BENDING | MPa |
| 2 | TRAILING EDGE TORQUE | MPa |
| 3 | LEADING EDGE BENDING | MPa |
| 4 | CENTRE TORQUE | MPa |
| 5 | TRAILING EDGE BENDING | MPa |
| 6 | LEADING EDGE TORQUE | MPa |
| 7 | SLIDING BLOCK FORCE | kN |
| 8 | SHAFT THRUST | kN |
| 9 | SHAFT TORQUE | kN.m |
| 10 | SERVO OIL PRESSURE | bar |
| 11 | AFT PORT PROBE | mm |
| 12 | AFT TOP PROBE | mm |
| 13 | FUEL RACK | mm |
| 14 | FWD STRB PROBE | mm |
| 15 | SHAFT RATE PULSE | volt |
| 16 | PROPELLER PITCH | deg |
| 17 | SHIP SPEED | m/s |
| 18 | RUDDER ANGLE | deg |

### CALCULATED QUANTITIES

| | | |
|---|---|---|
| 19 | BENDING MOMENT | kN.m |
| 20 | SPINDLE TORQUE | kN.m |
| 21 | FORCE | kN |
| 22 | RADIAL LOCATION | m |
| 23 | CIRCUMFERENTIAL LOCATION | m |
| 24 | BENDING MOMENT (FILTERED) | kN.m |
| 25 | SPINDLE TORQUE (FILTERED) | kN.m |
| 26 | FORCE (FILTERED) | kN |
| 27 | RADIAL LOCATION (FILTERED) | m |
| 28 | CIRCUMFERENTIAL LOCATION (FILTERED) | m |
| 29 | AFT HORIZONTAL | mm |
| 30 | AFT VERTICAL | mm |
| 31 | FORWARD HORIZONTAL | mm |
| 32 | FORWARD VERTICAL | mm |
| 33 | FFT | |
| 34 | SHAFT SPEED | RPM |
| 35 | FILTERED CHANNEL DATA | |

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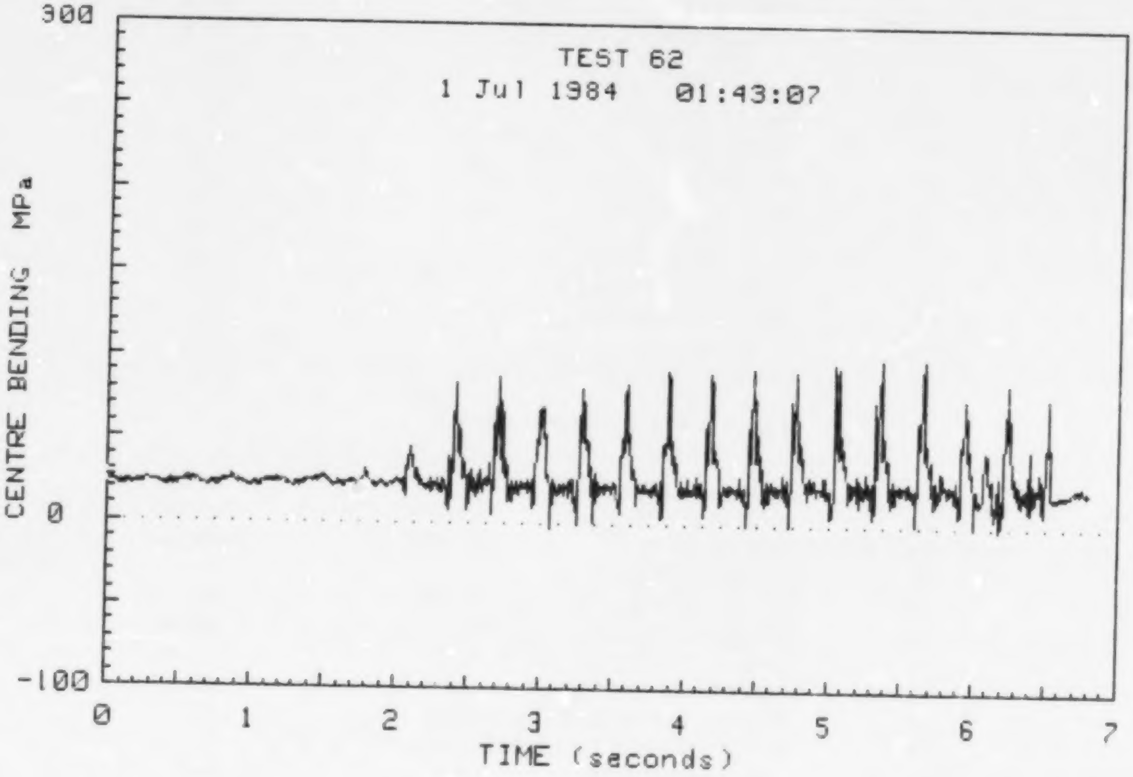
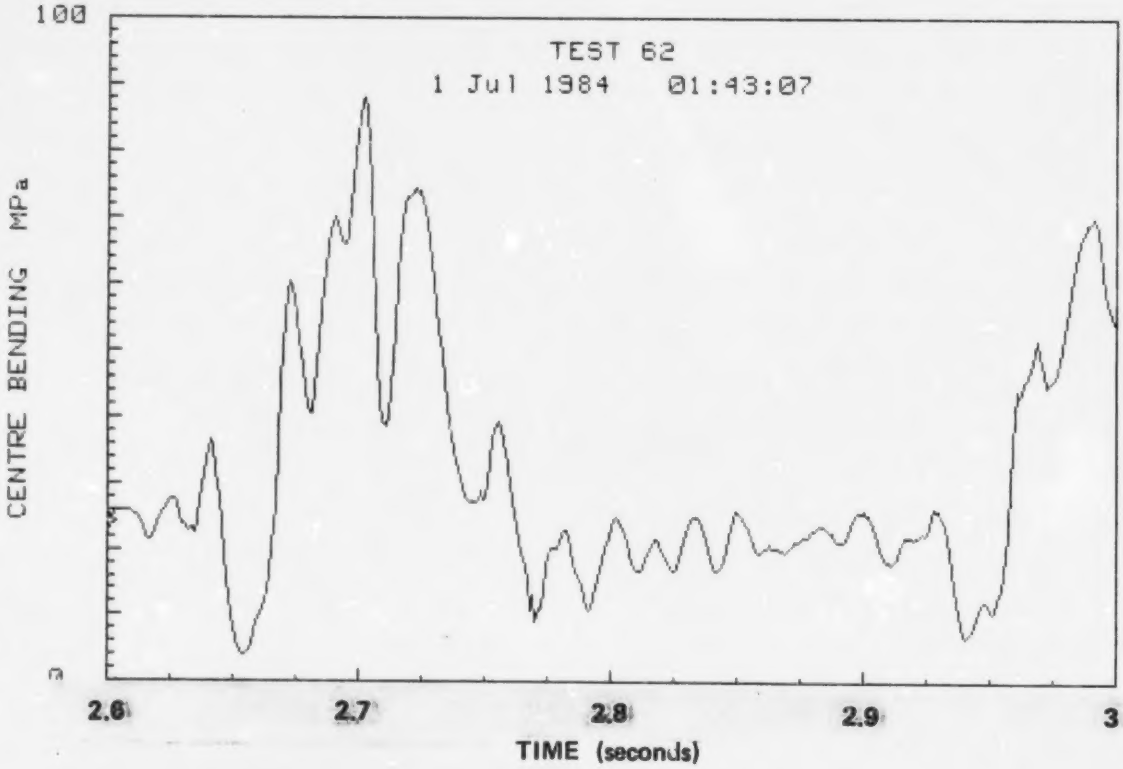
TITLE:
ACQUIRED AND CALCULATED
QUANTITIES

FIGURE No. 5.2.1



| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: CENTRE BENDING 7s WINDOW |
|---|---|---|
| | | FIGURE No. 5.2.2 |

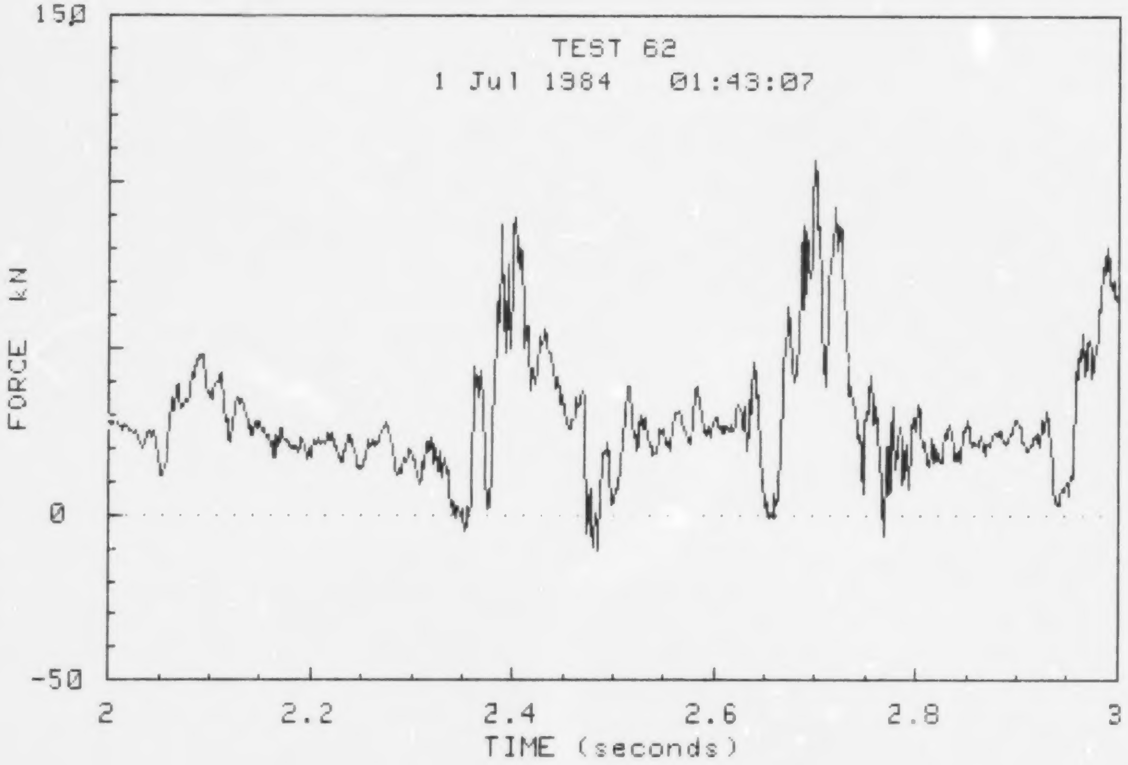


**CANADIAN MARINE DRILLING LIMITED**

MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE:
CENTRE BENDING 0.4s WINDOW

FIGURE No. 5.2.3



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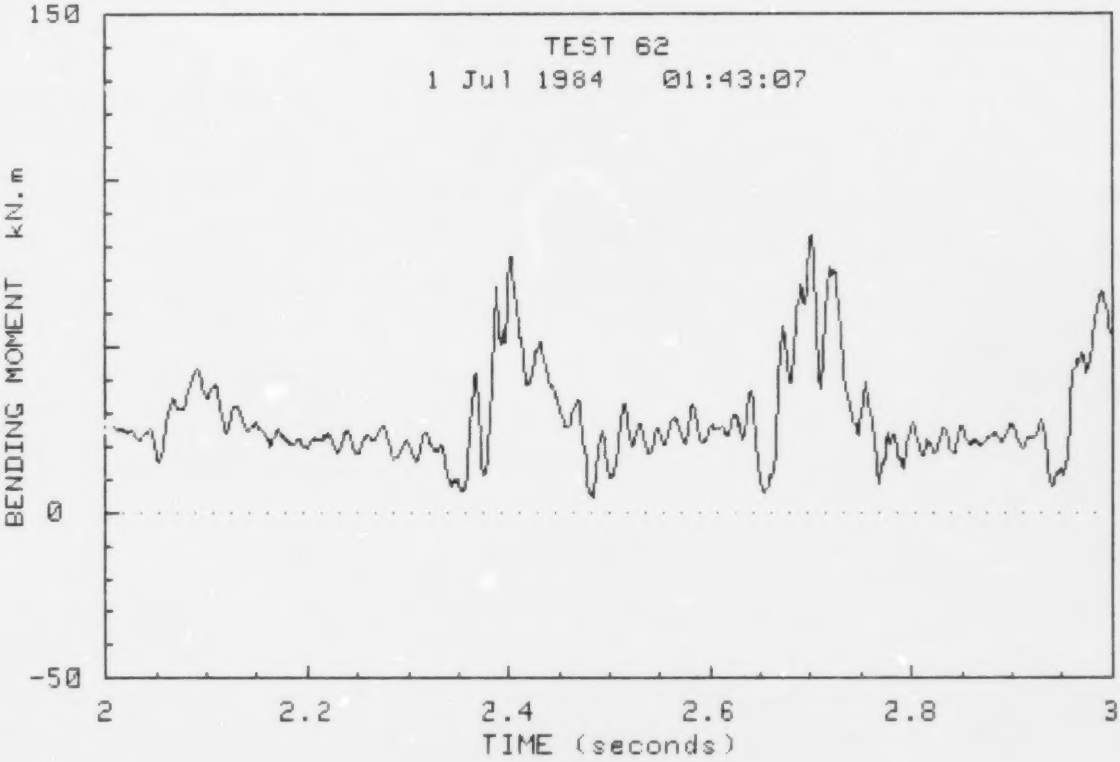
LIMITED

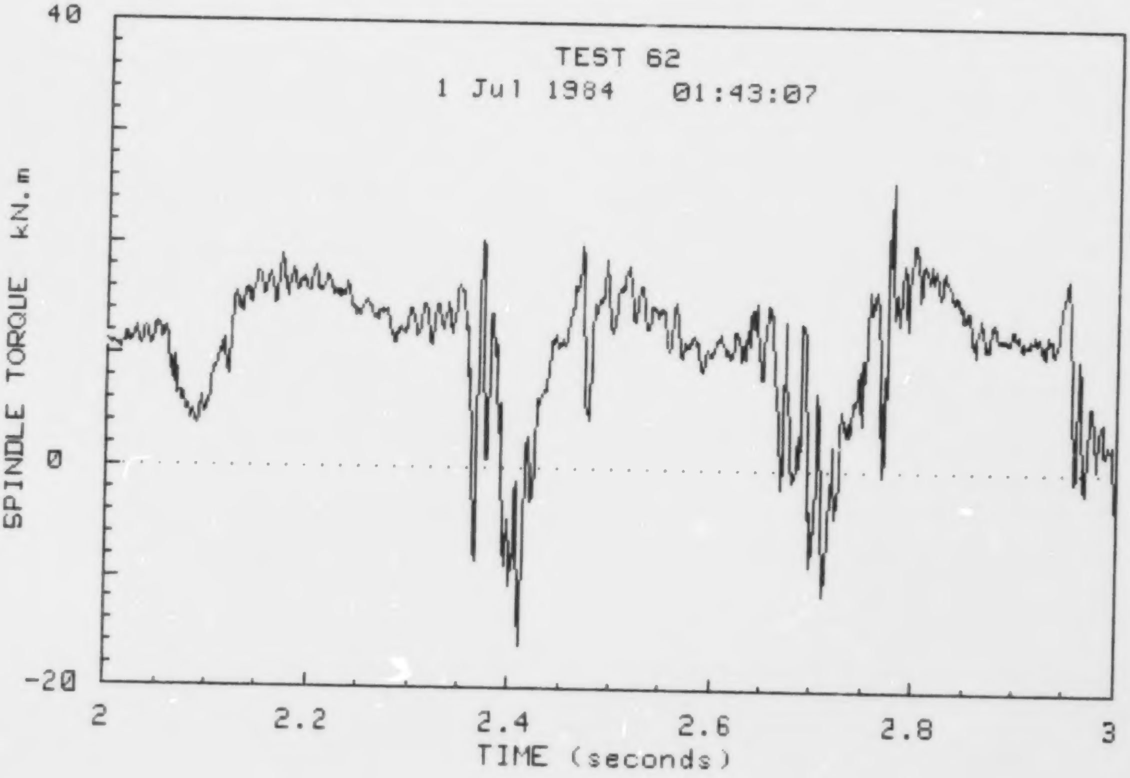
MEASUREMENT OF ICE
PROPELLER INTERACTION
PARAMETERS

TITLE:
BLADE FORCE

FIGURE No. 5.2.4



| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE:<br>BLADE BENDING MOMENT |
| | | FIGURE No. 5.2.5 |

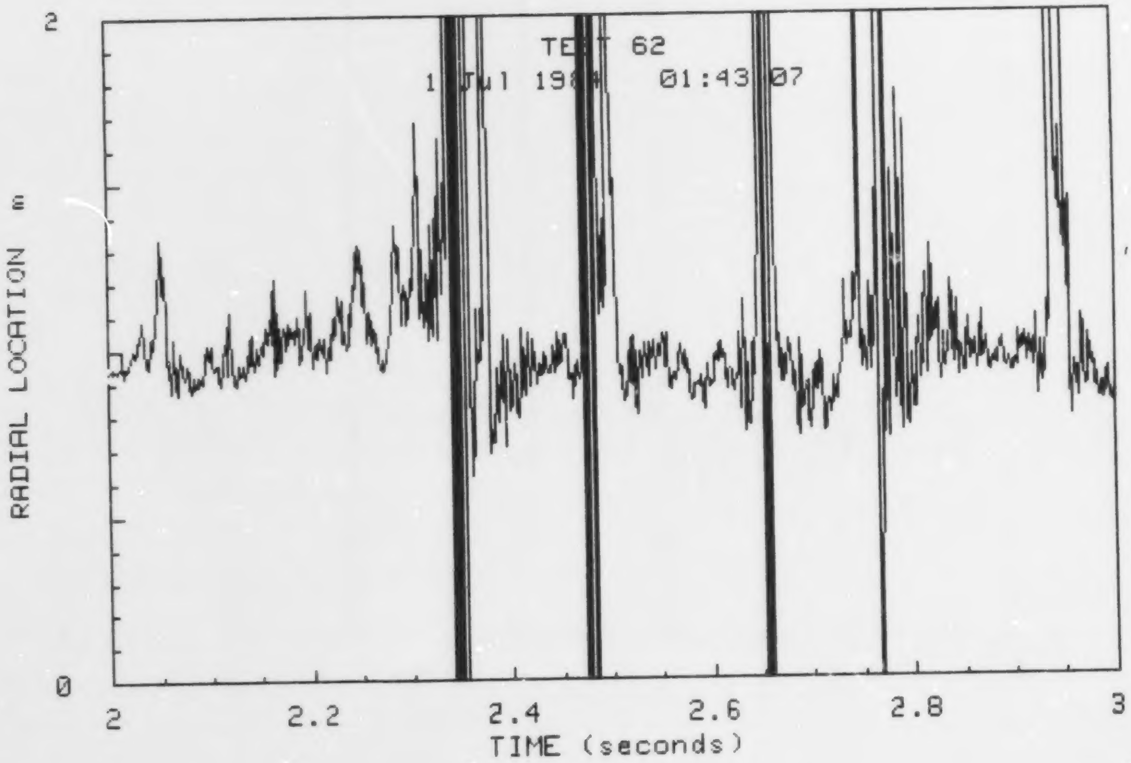


**CANADIAN MARINE DRILLING LIMITED**

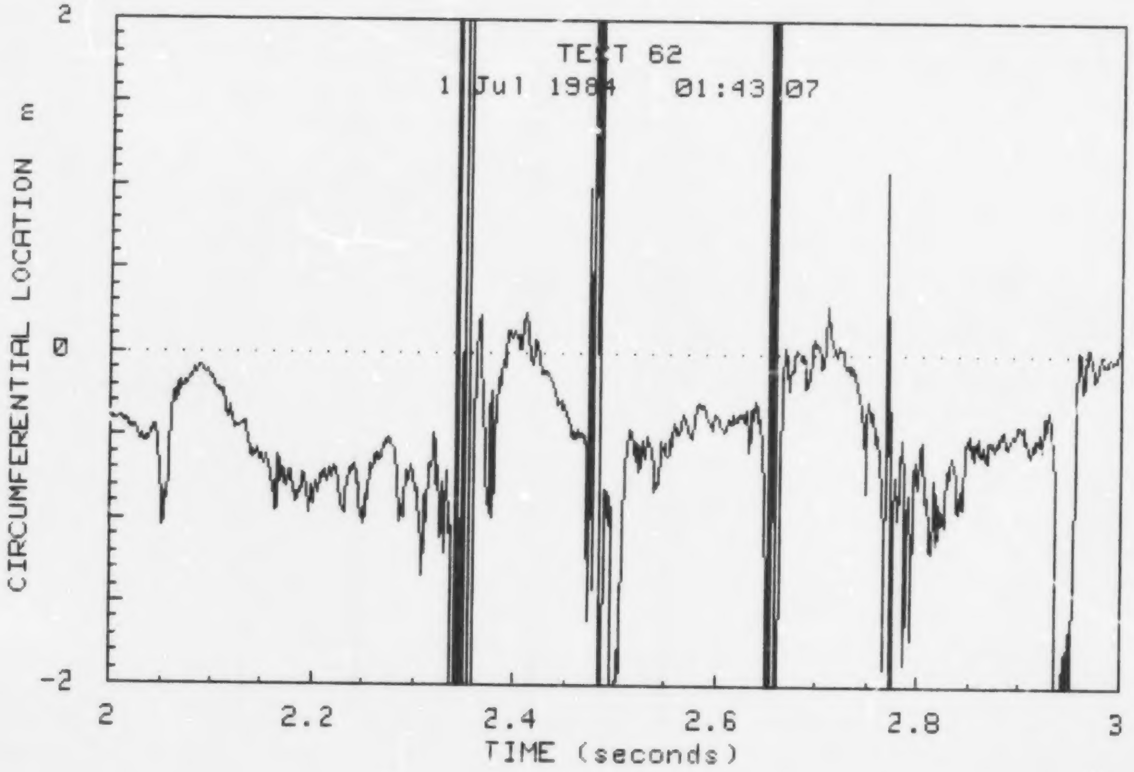
**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** **BLADE SPINDLE TORQUE**

**FIGURE No. 5.2.6**



| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: LOAD RADIAL LOCATION |
|---|---|---|
| | | FIGURE No. 5.2.7 |



**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** **LOAD CIRCUMFERENTIAL LOCATION**

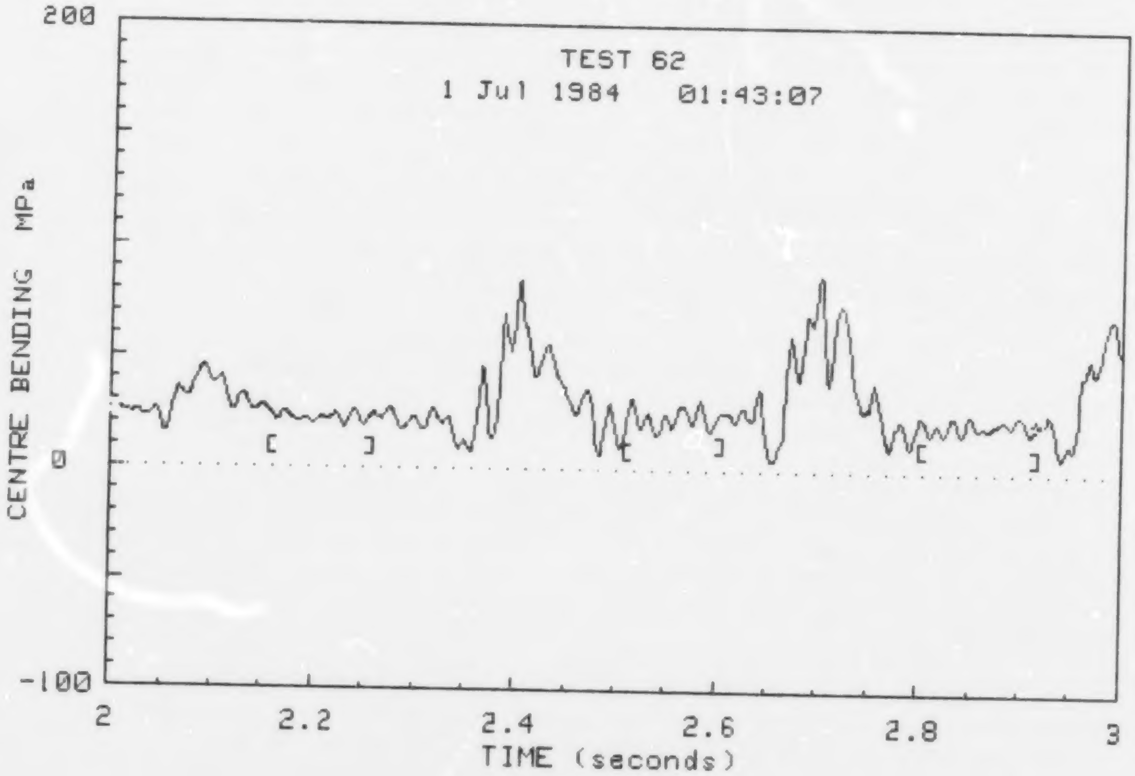
**FIGURE No. 5.2.8**

illustrated by Figure 5.2.9. This figure depicts a one second segment of the Center Bending data. There are three sets of brackets shown. The regions between the user selected brackets are assumed to represent the hydrodynamic baseline. The mean value of the signal within each set of brackets is calculated and between brackets a linear interpolation is performed. A linear extrapolation is performed from the outer brackets to the edge of the viewed data. This baseline is then, point by point, subtracted from the total signal (and similarly the other five blade signals). Finally, the influence coefficient matrix [A] is used to calculate the various forces. The result for the case of out-of-plane force is shown in Figure 5.2.10. This data can be compared with that presented in Figure 5.2.4 to see the effect of the removal of the hydrodynamic baseline.

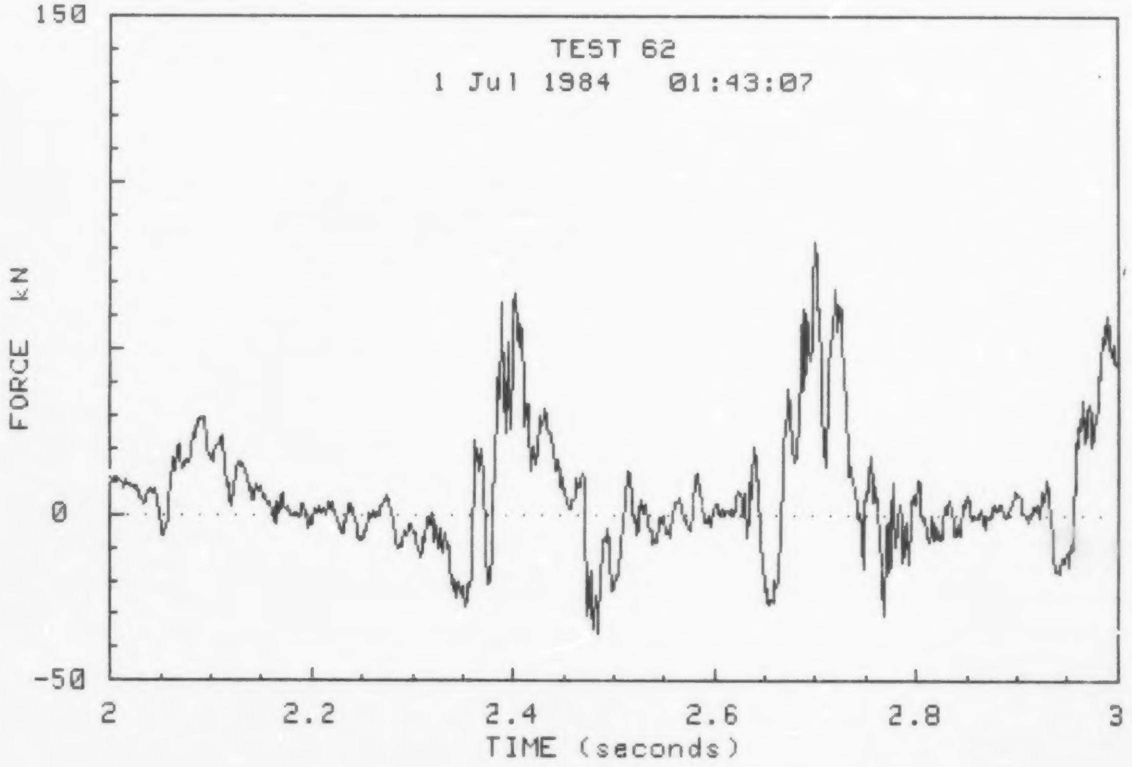
The performance of the digital filter (Ref 5.1) is illustrated by Figure 5.2.11. For this figure, data at frequencies higher than approximately 40 Hz have been removed (compare this data with Figure 5.2.10). The program has code which enables the user to select the parameters of the non-recursive low pass filter. For example, the following parameters could be chosen; A ripple in the pass band; A rejection ratio at frequencies greater than the cut off frequency, and; The width, in frequency, units, of the transition region between the pass band and the pass reject zone. In the case illustrated in Figure 5.2.11 we have ripple 0.1 db, reject ratio 40 db, upper limit of the pass band 40 Hz, and lower limit of the reject band 50 Hz. All of these parameters can be adjusted appropriately for the signal under investigation.

There are two broad classes of digital filters, recursive and non-recursive (Refs 5.1 and 5.2). Generally the recursive filters are more straight forward in design. For the application required in this project, a filter with low ripple in the pass band and a narrow band cut off was necessary. The computation time for the non-recursive type is essentially proportional to the length of the data set and to the ratio of the transition zone to the sampling frequency. From an analysis of non-recursive digital filters (Ref 5.1 and 5.2), a two stage filter could be made which was more computationally efficient than a single, one step design. Incorporated in "ANALYZE" are a prefilter which removes frequencies greater than 125 Hz and a post filter which provides the final designed characteristics.

As an additional guide to filtering the data and investigating the behaviour of the data in the frequency



| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | **TITLE:** CENTRE BENDING - HYDRODYNAMIC BASELINE |
| | | **FIGURE No.** 5.2.9 |

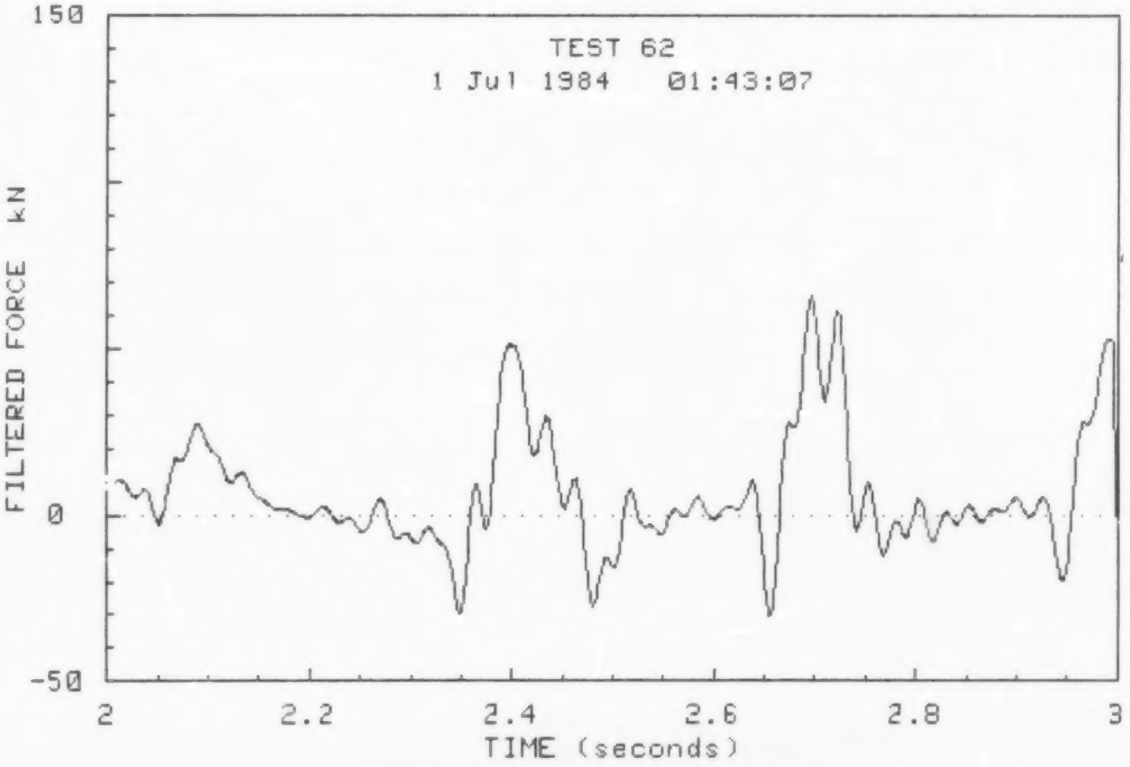


**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** **BLADE FORCE - HYDRODYNAMIC BASELINE**

**FIGURE No.** 5.2.10



| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | **TITLE:** **BLADE FORCE - FILTERED 40 Hz** |
| | | **FIGURE No. 5.2.11** |

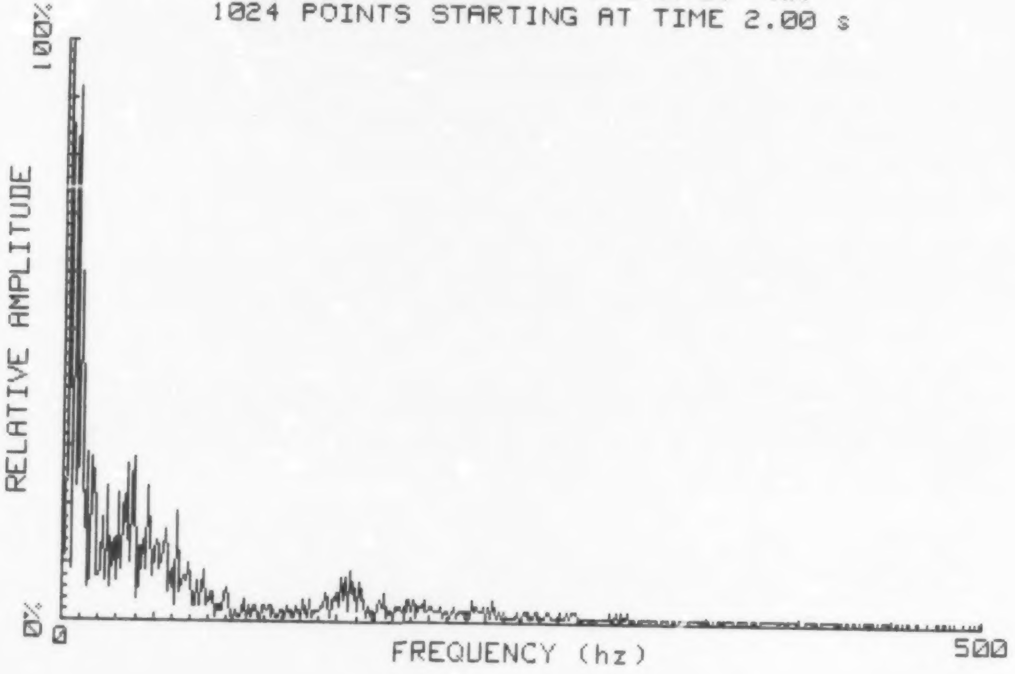
domain, a Fast Fourier Transform (FFT) (Ref 5.1) algorithm was incorporated into the code. Figure 5.2.12 illustrates the FFT of the data displayed in Figure 5.2.10, and the lower frequency portion of the FFT in Figure 5.2.13.

The last major aspect of the analysis capability was the display of the shaft movement data. A one second segment of this data is shown in Figure 5.2.14 for the aft-most probe situated on the port side of the bearing. The increase of vibratory amplitude between approximately 3.95 and 4.2 seconds is believed to be associated with ice/propeller interaction. A second probe was mounted near the upper portion of the aft bearing. The data shown in Figure 5.2.15 is that one second of data showing the locus of the propeller shaft relative to the bearing. The circle indicates a movement of 0.7 mm. The user could view any time segment of the probe data displayed in x-y format, for example all seven seconds of data and also 'step' through the data at a user selectable rate. This latter feature allowed the user to view the time history of the shaft movement.

Other utility features provided were: The ability to print the graphic image on a Hewlett Packard HP 2671G thermal printer; A cursor driven facility for displaying the time in seconds, and; The ability to display a value in units of an element of the displayed data.

For the normal time domain data, the user could overlay as many signals on the screen as were desired thereby facilitating the investigation of the correlations between the acquired data signals.

TEST 62
FFT of FORCE
MAXIMUM AMPLITUDE = 1.07E+01 kN
1024 POINTS STARTING AT TIME 2.00 s

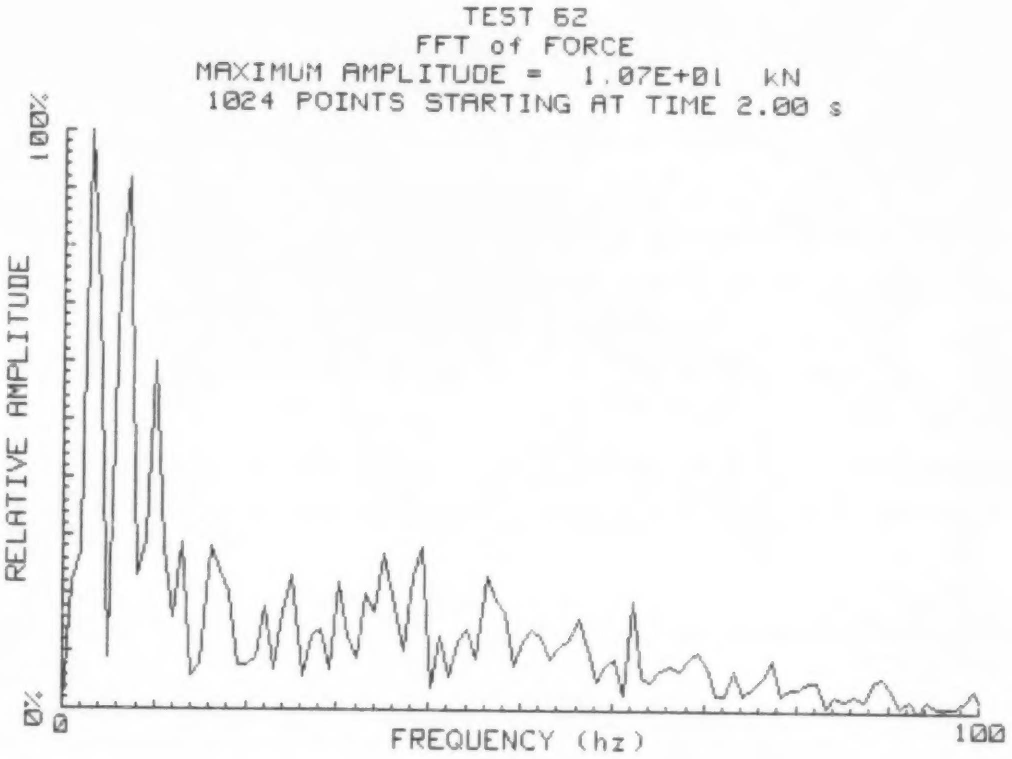


**CANADIAN MARINE DRILLING LIMITED**

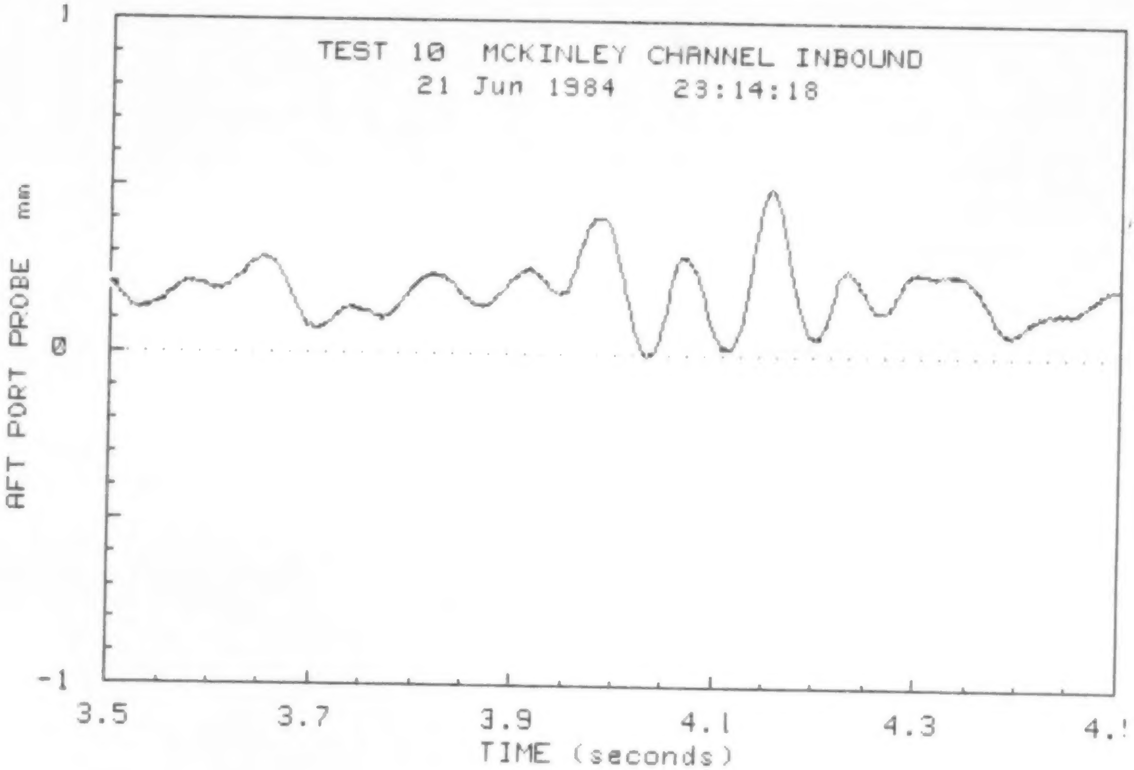
**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:**
**FFT OF BLADE FORCE 500 Hz**

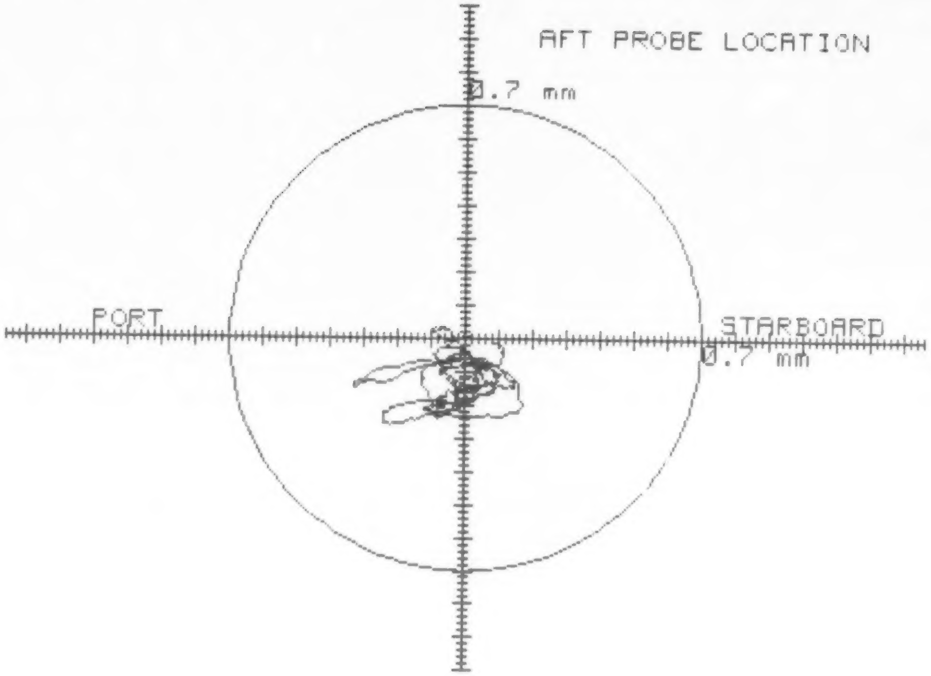
**FIGURE No. 5.2.12**



| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | **TITLE:** **FFT OF BLADE FORCE 100 Hz** |
| | | **FIGURE No. 5.2.13** |



| | | |
|---|---|---|
| **CANADIAN MARINE DRILLING LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | **TITLE:** **AFT PORT PROBE SIGNAL** |
| | | **FIGURE No. 5.2.14** |



**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:**

**X-Y PLOT OF AFT MOVEMENT**

**FIGURE No. 5.2.15**

# 6. FIELD TEST PROGRAM

## 6.1 General Comments

The 1984 field test programme took place during the early break-out from McKinley harbour with the objective of obtaining physical measurements from which ice induced loads on the propeller system of the MV Robert LeMeur could be determined. These measurements would then be related to the current ice conditions to develop an understanding of the ice/propeller interaction phenomena, and would ultimately be used in the generation of design criteria and regulations.

Prior to break-out, the MV Robert LeMeur was in the Canmar Careen drydock where the necessary instrument and transducer installations were completed. At the same time the calibrations of the transducers, including the propeller blade, the yoke sliding block and the shaft movement probe were carried out. The data acquisition system was put in place and refinements to the software were made.

Ice conditions and Canmar fleet operational logistics indicated that break-out of the fleet should take place sometime after June 20. The test team consisting of Paul Spencer, Vlodek Laskow, Merv Edgecombe, John Shaw, Shawn Cornett of Canmar, Bill MacLaren from the Transportation Development Centre, and Clark Norris of the Arctic Ship Safety Branch of the Coast Guard Northern were onboard the MV Robert LeMeur on June 21. However, mechanical operations problems with the ship caused the sailing to be postponed by a week and the actual field trials began on June 30. For the latter time period, Ian Bayly represented the Transportation Development Centre.

Data collection continued until July 04 by which time 343 events had been recorded by the digital data acquisition system. By the end of the test period approximately 50% of the events had been visually inspected using the "ANALYZE" computer program and a representative sample of data including calculations of blade forces. Fast Fourier Transforms of data, digital filtering and shaft probe movement data had been printed in hard copy.

Visual observations of the current ice conditions were made from the vessel and detailed observations of the wake of the vessel from the stern were made. Ice conditions did not permit standing on the ice for clear examination. In addition to this the tests were performed during the normal activities of the vessel, which precluded stopping the ship for detailed ice properties analysis.

The remaining parts of this chapter describe the performance of the equipment, the ice conditions and properties and the observations from the stern.

## 6.2 Ice Conditions And Characterization

The 1984 MV Robert LeMeur propeller blade tests were conducted in late June and early July. The ship departed from the harbour via the McKinley Bay approach channel and continued to the Havik drill site location at approximately 70°20'N and 132°13'W. There it engaged in icebreaking activities in support of the Explorer II. Onboard observations of ice conditions were made throughout the testing period.

The propeller blade tests were designed to measure ice impact forces on an instrumented propeller. In order to index the observed forces and provide a comparison between the results of different tests, it was necessary to characterize the ice strength and block size distribution wherever possible. During the 1983 tests, temperature and salinity measurements of ice were collected and brine volumes determined. These were then related to ice strength (Ref 6.1).

### 6.2.1 General Ice Conditions

Climatic conditions in the southern Beaufort Sea were near normal for the winter of 1983-84 (Ref 6.2). Freeze-up had begun by the end of September and new ice growth continued into October. The polar pack was located 100 to 125 miles north of the Tuktoyaktuk Penninsula at that time. By the third week in October the majority of the Beaufort Sea was covered by ice. Temperatures remained normal to slightly above normal into April, causing ice growth to be slightly less than the mean. First year ice thickness off Cape Parry reached 155 cm, approximately 10% lower than the average mean thickness (Ref 6.2). Second year ice which had drifted in from the polar pack during freeze-up, occurred as isolated floe fragments in the area.

Temperatures in May and June increased to 2°C above normal. This accelerated spring runoff and the deterioration of the ice cover. Breakup of the landfast ice in the southeastern Beaufort Sea normally occurs around July 8-15. In 1984 however, breakup took place between June 22 and June 28, beginning with the fracturing of the ice sheet off Tuktoyaktuk Penninsula and the clearing of the Mackenzie Delta.

Local air temperatures during the testing program averaged 3° to 5°C and the sky was often overcast with occasional precipitation. The winds were light to moderate.

### 6.2.2 Ice Characterization

The ice encountered during the propeller blade tests was characteristic of the type of ice found in the southern Beaufort Sea immediately after breakup. The ice occurred primarily as vast or giant floes (2 to 10 km in diameter) and the overall regional concentration was 6 to 8 tenths. The floes were made up of numerous smaller pans of ice loosely joined together. Melt pools extending through the ice, comprised 20% to 30% of the area of a vast floe. The ice conditions during each of the 343 tests, where available, are listed in Appendix B of the Final Report. Three general types of ice were identified during the tests and are described in the following sections.

### 6.2.3 First Year Level Ice

The level ice in the area was quite deteriorated and had an average freeboard of 15 to 30 cm indicating an average thickness of 60 to 120 cm. There were many melt ponds which extended through the total ice thickness. This allowed sea water to come into contact with large areas of the floe surface raising the surface ice temperature to the ambient sea temperature, approximately -1°C. In addition, the ambient air temperature averaged +3°C during the tests, further warming the ice. The mean ice temperature was estimated to be -1°C.

First year ice with a thickness of 60 to 120 cm would be expected to have an average salinity of 6-7 ppt according to Cox and Weeks, (Ref 6.3). The ice appeared to be very granular in structure suggesting that severe brine drainage had taken place. The brine channels would however, be open to influxes of sea water (the average salinity in the Beaufort Sea is 30 ppt) further reducing the ice strength (Ref 6.4). The mean salinity of the ice is, therefore, estimated to be between 10 and 20 ppt. The resultant brine volume, calculated using an equation derived by Frankenstein (Ref 6.5), was found to be in the range of 50 to 120 ppt. Ice strength is related to brine volume following the curve shown in Figure 6.2.1 and it was, based on the curve, subsequently estimated that the uniaxial unconfined crushing strength of the first year level ice was in the order of 0.2 MPa.

### 6.2.4 First Year Ridges

Due to the nature of the work required from the Robert LeMeur which was to breakup threatening ice floes in order to safeguard the operation status of the drillships, much of the ice propeller interaction was with the first year ridge ice. Although the ridges were in a moderately deteriorated state with rounded surfaces, the sails varied between 0.5 and 2.0 m in height with total thicknesses, therefore, averaging 2.0 to 8.0 m (Ref. 6.6).

A strong interdependence between average salinity and ice thickness has been found by Cox and Weeks (Ref 6.3). Based on their findings, the mean salinity of the first year ridges was estimated to be about 5.0 ppt for a 2 m ridge and 1.0 ppt for a 8.0 m thick ridge. The temperature of the ridges would have been somewhat lower than that of the level ice and it was estimated that the temperature would average -30°C. The brine volume was consequently calculated to be between 0.01 ppt and 0.04 ppt. The determination of the crushing strength of the ice resulted in values of 0.9 MPa for a 2.0 m thick ridge and 1.2 MPa for an 8.0 m thick ridge.

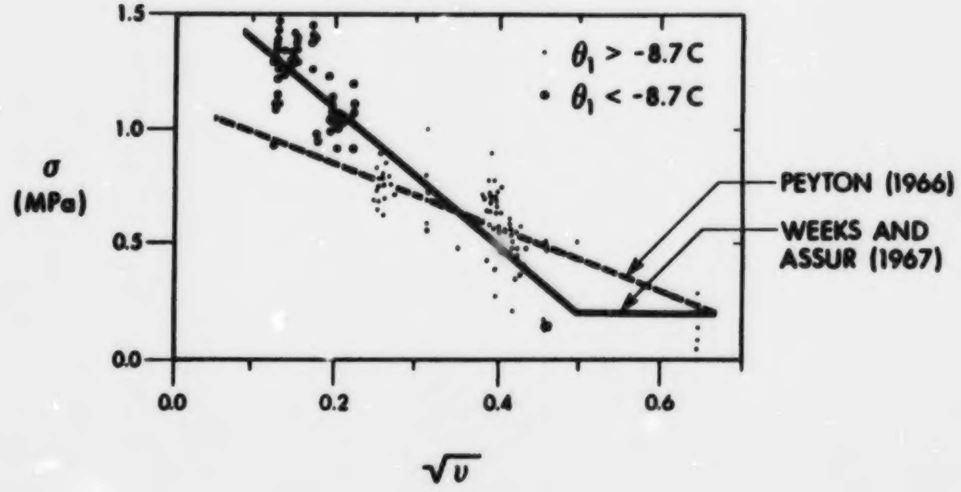
### 6.2.5 Second Year Ice

Isolated second year floe fragments embedded in the first-year ice were observed on several occasions. They were in the order of 50 to 150 m in diameter with smooth surficial topographies. They were blue/turquoise in colour and had occasional shallow melt ponds on the surface. The average freeboard was between 1.5 and 2.5 m giving a mean thickness of 5.5 to 9.0 m (based on a keel to sail ratio of 3.5:1, Reference 6.6).

The mean temperature of the second year ice was estimated to be -4°C. The salinity would have been low, on average 1 ppt. The estimated brine volume was, therefore, calculated to be 0.05 ppt. Consequently, the crushing strength of the second year ice was estimated to be approximately 1.2 MPa.

### 6.2.6 Conclusions

The ice conditions during the MV Robert LeMeur propeller blade impact tests in June - July, 1984, were



ICE STRENGTH σ FROM COMPRESSION TESTS ON SEA ICE VS. SQUARE ROOT OF THE BRINE VOLUME

| | | |
|---|---|---|
| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: RELATIONSHIPS BETWEEN SEA ICE STRENGTH FROM COMPRESSION TESTS VS SQUARE ROOT OF THE BRINE VOLUME<br>FIGURE No. 6.2.1 |

typical of late breakup in the southern Beaufort Sea and are summarized in Table 6.2.1. The ice existed in vast or giant floes made up of approximately 7-8/10 first year level ice, 1/10 first year ridges, less than 1/10 second year ice and 1-2/10 open water. The majority of the ice was deteriorated with no snow cover and a high concentration of melt ponds. The warm ice temperatures and moderate salinities resulted in moderate to high brine volumes. The crushing strengths of the various ice types ranged from 0.2 MPa for first year level ice to 1.2 MPa for thick first year ridges and second year ice. Because of the nature of the icebreaking activities which were being carried out by the MV Robert LeMeur during which the propeller blade impact tests took place, it is estimated that the majority of the impacts were a result of thick first year ice with moderate to high crushing strengths in the range 0.6 to 1.2 MPa. The photographs in Figures 6.2.2 to 6.2.8 show examples of the ice conditions encountered during the field tests.

## 6.3 Observations Of The Wake Of MV Robert LeMeur During Ice/Propeller Impact Tests

Sample channel conditions in the wake of the ship are shown in Figures 6.3.1 to 6.3.4.

- When going through the channel in the deteriorating ice field, ice block sizes were much larger than those generated during level ice breaking, since the blocks were loose. Size frequently observed was 2 * 2 * 3 m, 2 * 3 * 5 m, (estimated visually).

- Many blocks came up with large indents on their edges, as if they had hit the nozzle or the ice clearing propeller island.

- Large blocks (approx. $10m^3$) came up to the surface several ship lengths after exiting the ice field. They, therefore, may have been sitting on the appendages until the propeller pitch was reversed.

- Milled pieces were visible in the wake exiting the nozzle with high speed. Most of them were "fist" size but some larger ones with triangular shape (0.1 * 0.3 * 0.5 m) were also seen.

- The largest piece believed to be milled was 0.2 * 0.3 * 0.5 m.

- Milling was clearly audible while standing on the aft deck.

| ICE TYPE | THICKNESS (cm) | MEAN TEMPERATURE (°C) | MEAN SALINITY (ppt) | MEAN CRUSHING STRENGTH (MPa) |
|---|---|---|---|---|
| First-year level ice | 60 to 120 | -1 | 10 to 20 | 0.2 |
| First-year level ice | 200 | -2 | 5 | 0.9 |
| First-year ridges | 800 | -4 | 1 | 1.2 |
| Second-year ridges | 550 to 900 | -4 | 1 | 1.2 |

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MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE: CHARACTERISTICS OF ICE OBSERVED DURING ROBERT LEMEUR PROPELLER BLADE TESTS JUNE - JULY 1984

TABLE 6.2.1

FIGURE 6.2.2
TYPICAL ICE, INCLUDING SOME FIRST-YEAR RIDGES,
DURING THE LEMEUR 1984 FIELD TESTS

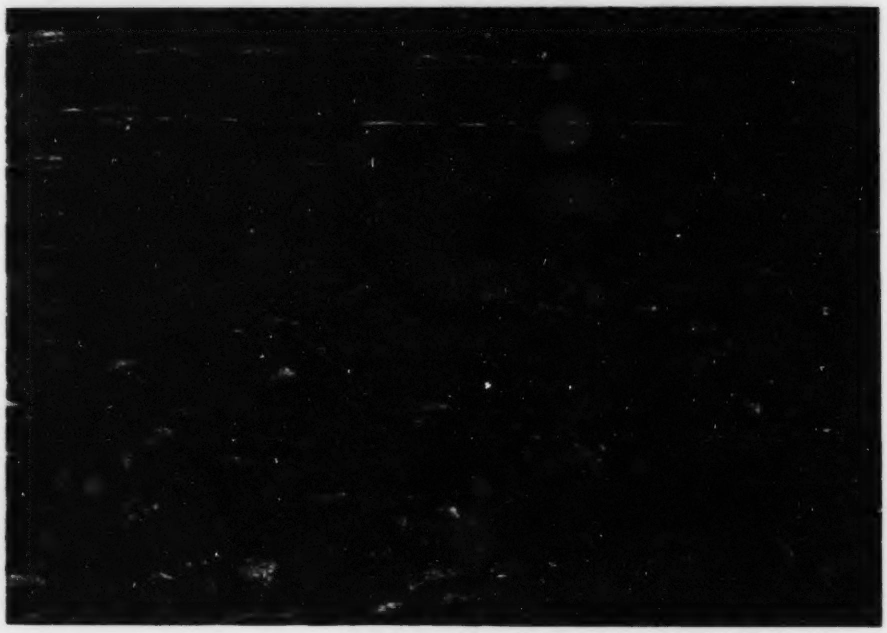


FIGURE 6.2.3
TYPICAL ICE CONDITIONS, EARLY JULY 1984. N.B. DEEP
INTERCONNECTED MELTPOOLS AND FIRST-YEAR RIDGE

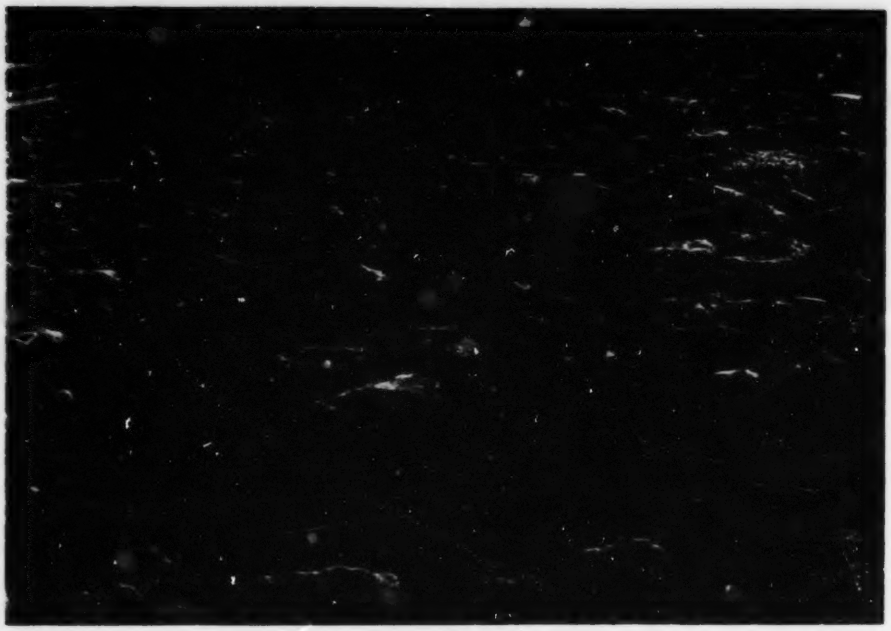


FIGURE 6.2.4
BROKEN CHANNEL CONDITIONS FROM THE STERN OF THE LEMEUR,
EARLY JULY 1984

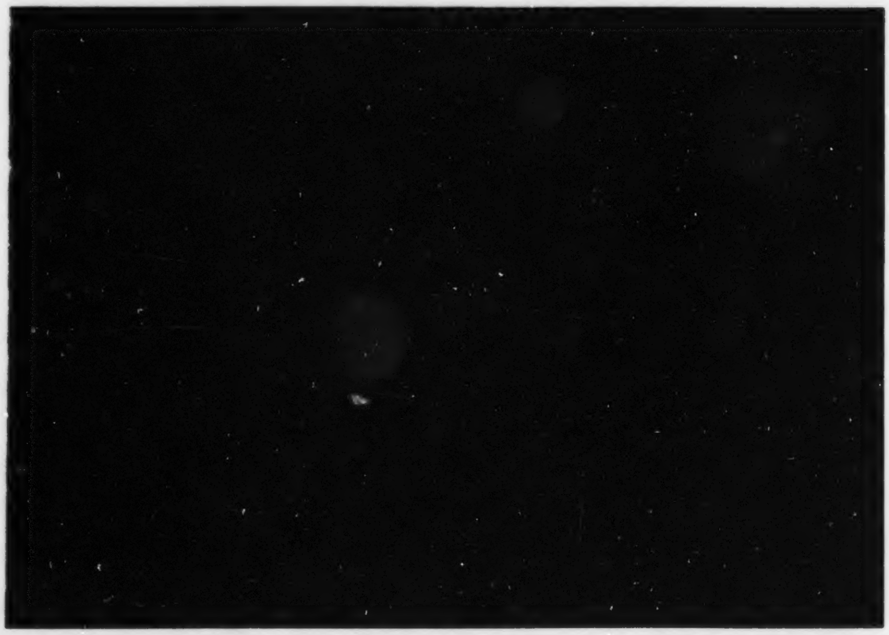
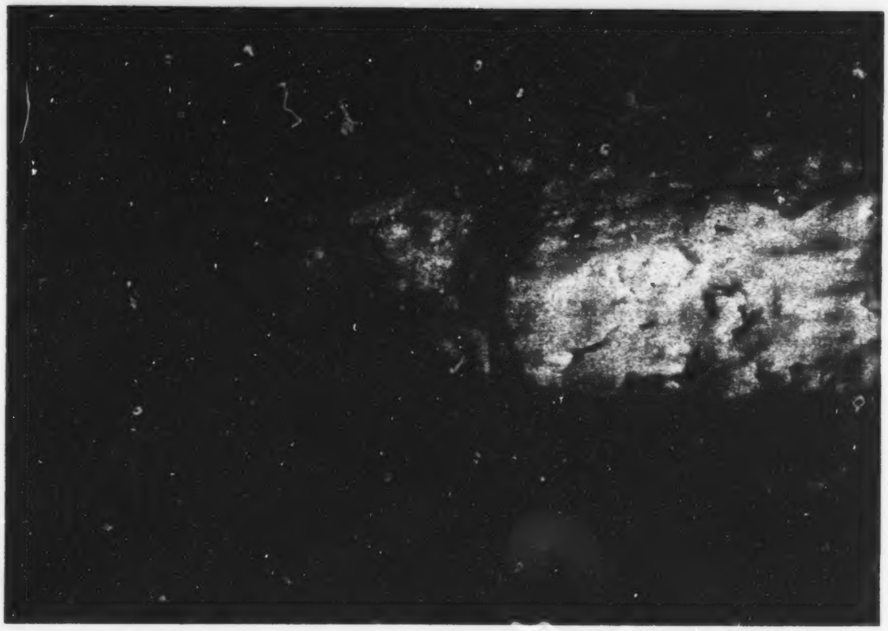


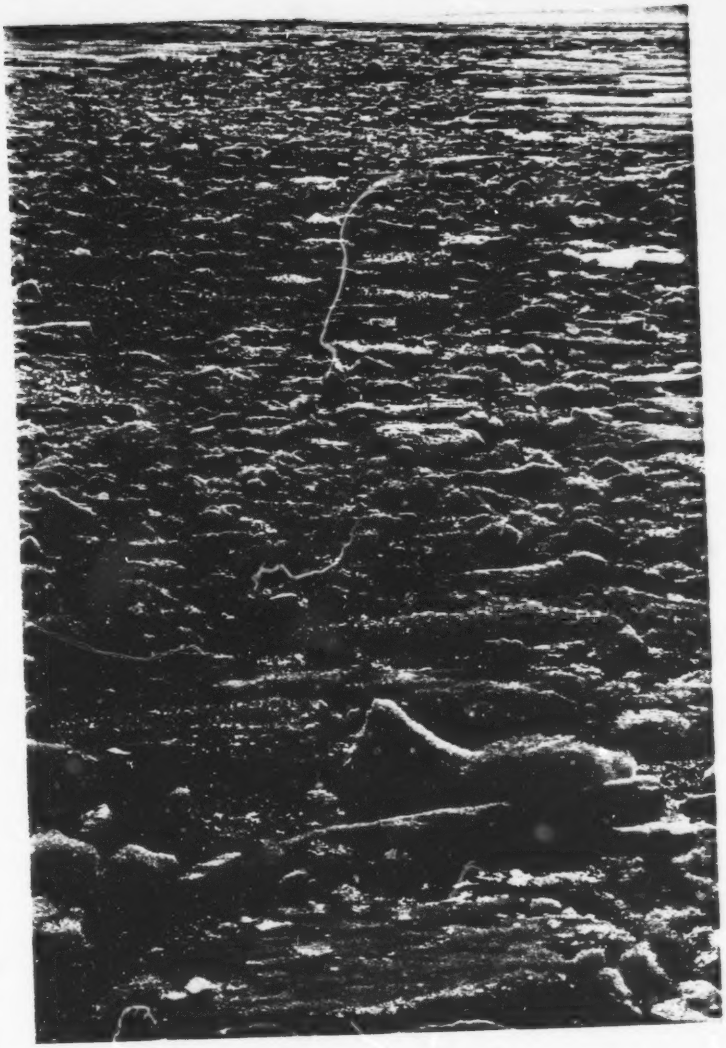
FIGURE 6.2.5
BROKEN CHANNEL CONDITIONS FROM THE BOW OF THE LEMEUR,
WHILE REVERSING AFTER A RAM

FIGURE 6.2.6
BROKEN CHANNEL CONDITIONS WHILE TRANSITING SEVERELY DETERIORATED FIRST-YEAR ICE WITH HIGH CONCENTRATIONS OF MELTPOOLS

FIGURE 6.2.7
BREAKING FIRST-YEAR DURING THE LEMEUR FIELD TESTS, EARLY JULY 1984. N.B. EXPLORER II IS VISIBLE



| | | |
|---|---|---|
| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: BREAKING A FIRST-YEAR RIDGE APPROXIMATELY 2m THICKNESS, LEMEUR FIELD TESTS, EARLY JULY 1984 |
| | | FIGURE No. 6.2.8 |



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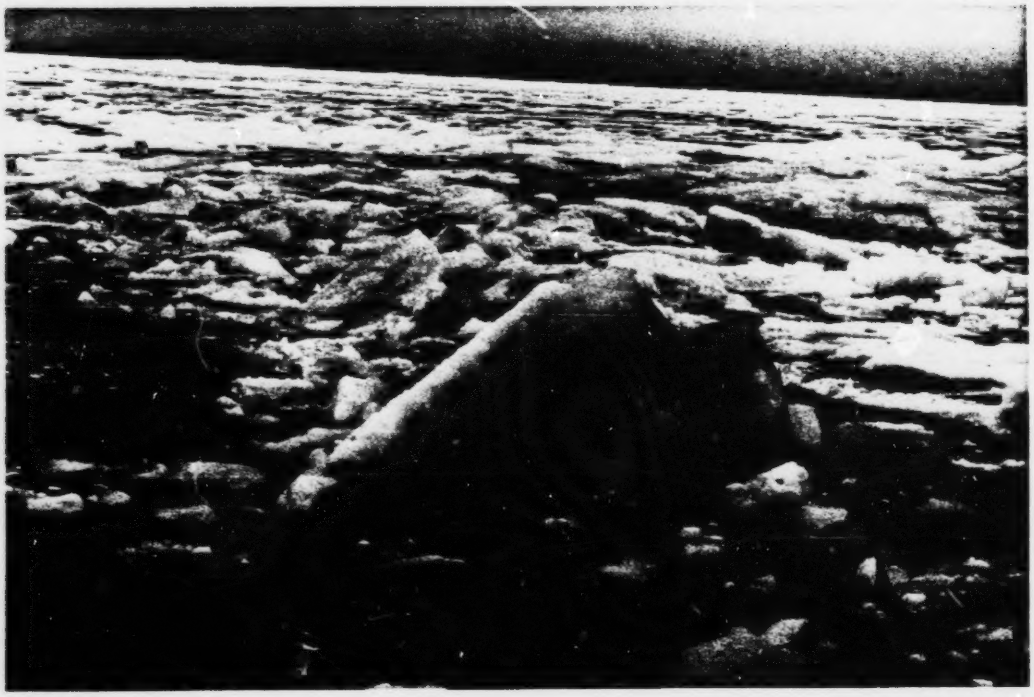
MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE: CHANNEL CONDITIONS ASTERN OF THE ROBERT LEMEUR OUTSIDE OF MCKINLEY HARBOUR, JULY 2, 1984

FIGURE No. 6.3.1



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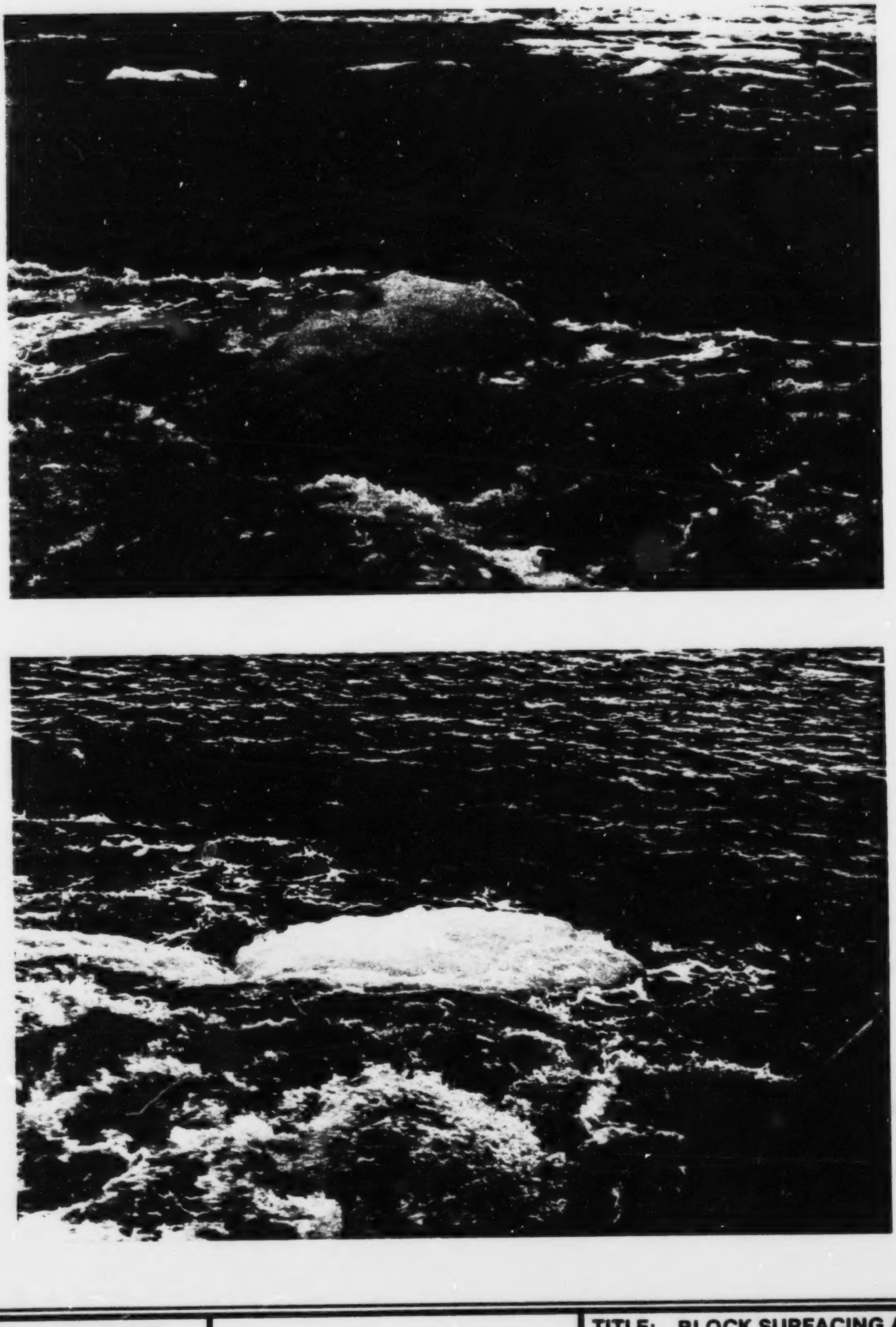
MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE:CHANNEL CONDITIONS ASTERN OF THE ROBERT LEMEUR OUTSIDE OF MCKINLEY HARBOUR, JULY 2, 1984

FIGURE No. 6.3.2



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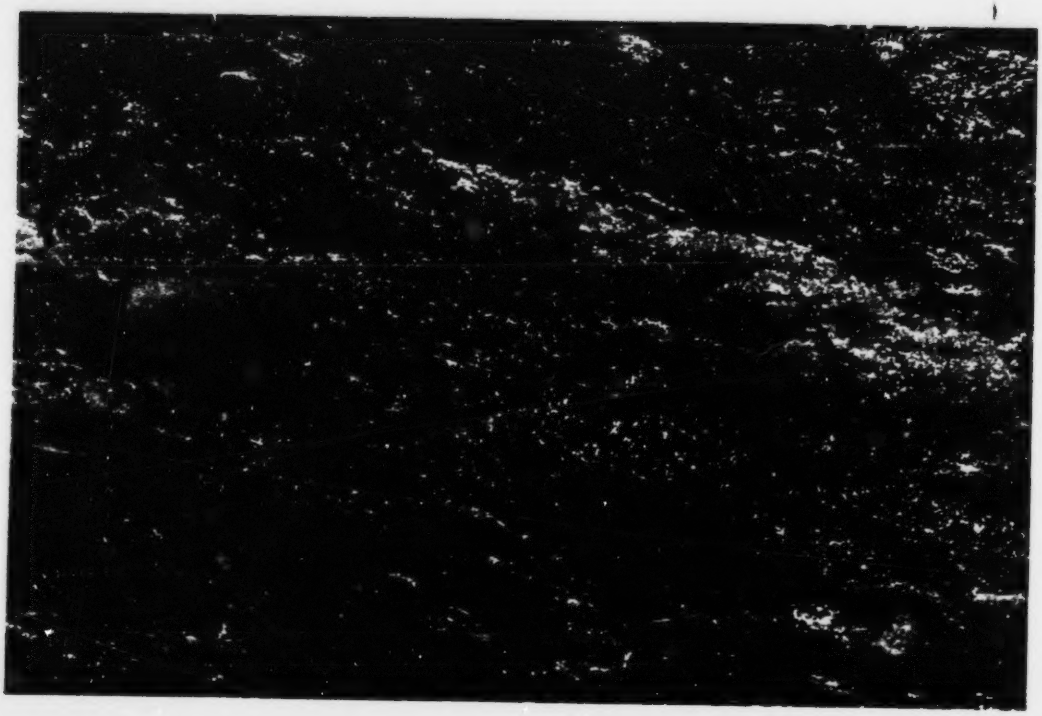
MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE: BLOCK SURFACING AFTER BEING ENTRAPPED IN THE SHIP'S APPENDAGES

FIGURE No. 6.3.3



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|---|---|---|
| **CANADIAN<br>MARINE<br>DRILLING<br>LIMITED** | **MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS** | **TITLE:<br>MILLED ICE PIECES ASTERN OF THE ROBERT LEMEUR, JULY 2, 1984** |
| | | **FIGURE No. 6.3.4** |

- Occasionally rebound hits were heard when an ice piece was hitting the nozzle's surface.

- Prolonged milling was always associated with large disturbances of the wake. The wake deteriorated and turned into turbulent "white water" which came up immediately aft of the stern.

- During overload conditions (slow speed, full power) many large ice blocks flowed forward into the nozzle from the edges of the channel.

- Ice clearing propeller island cleared large ice blocks very well. Such ice came up frequently without milling.

- Propellers (direction of rotation inward) took ice blocks from the edges of the channel into the wake.

- From all of the interactions heard, none of them was composed of less than several hits.

- Long interactions (more than 5 sec.) were more frequent than the short ones.

- Due to the inward direction of rotation, there was a large suction field in the middle of the wake, which entrained ice taking ice with it.

- Propeller wash created ice free channel approximately 8 m wide.

- Slipstream broke completely on large blocks.

- The estimated size of ice blocks in the ship's wake are:

Mean: 0.21 $m^3$

Extreme: 21.0 $m^3$

## 6.4 Performance Of Instrumentation

When MV Robert LeMeur undocked, all of the transducers were fully operational. Throughout the test program that followed, most of these, as well as the associated signal conditioning and data acquisition equipment, functioned as designed. The equipment problems and transducer failures that did occur are discussed in this section.

### 6.4.1 Blade Strain Gauges

The blade strain gauging system have been largely successful. Calibration of the blade, fully secured to the hub, gave linear and reproducible results. Differences in the calibration results compared with the original calibration done in 1982 in the laboratory suggested the importance of having the propeller base secured with all seven retaining bolts, as the number and distribution of these points of support evidently substantially affected the stress distribution within the blades. This was also supported by comparison of the 1982 results obtained in the laboratory, where only 2 of the seven retaining bolts were used, and the 1982 calibration checks done on the blade of the fully assembled and installed propeller in the ship builder's drydock.

The problems observed with the blade strain gauging systems were an intermittent signal from the trailing edge torque bridge for test event numbers 45 - 120 and an intermittent signal from the centre torque bridge, first detected in test event number 300 on the final day of data collection. For all of the blade strain gauge bridges, the impedances of the individual elements were observed to be stable, and isolation from the shaft remained above 20 megaohms throughout the tests. The constancy of the element impedance suggested that the measures taken to waterproof the strain gauge bridges were successful.

The intermittant signal observed in the centre torque bridge was due to an intermittant connection in one of the four lead wires connecting the bridge to the shaft signal conditioning. This was almost certainly due to the breaking of either the soldered connection between one of the lead wires and the gauge solder tab or, more likely, the fracturing of the foil resistive element where it was joined to the solder tab. Since the bridge did not exhibit the sort of drift that would be associated with gradual fatiguing of this connection, it was possible that fracture was caused by a single, very large strain or acceleration impulse at the gauge location.

### 6.4.2 Sliding Block

The sliding block instrumentation was known to be much more vulnerable than the blade strain gauging due to the exposed lead wires within the hub which had to accommodate the differential motion of the sliding block and the blade carrier during pitch changes. The first six ice impact events were recorded onboard the MV Robert LeMeur on June 20, during which time the sliding block instrumentation was fully functional and gave good data.

Prior to the beginning of data collection on the following day, however, one of the strain gauge lead wires from the sliding block became an open-circuit, thereby unbalancing the bridge. As a result, no sliding block data was obtained for Tests 7 through 12, which were carried out on June 21. Following the June 21 deployment the ship was shutdown in McKinley Bay for engine alignment work until June 30. During this time, the sliding block strain gauge connections to the shaft signal conditioning were modified to eliminate the open circuited element from the bridge. Instead of a four element full bridge, only two of the strain gauges in the sliding block were used, one under each load carrying face in a half bridge arrangement. Note, that in order to reconfigure the sliding block bridge it was necessary for the shaft rotation to be stopped.

Fortunately, such a failure of connections to the sliding block had been recognized as a possibility at the calibration stage and physical calibration of the block had been done for half bridge configuration as well as for the standard full bridge case.

The rewired half bridge continued to function from Test 13, carried out on June 30, to Test 67, carried out on July 1, inclusive. At this point, a second lead wire connection failed. No opportunity was had to make further repairs until after Test 113, obtained late in the afternoon of July 1. At this point, the sliding block bridge was again reconfigured at the shaft signal conditioner. As it was discovered that both of the strain gauge elements that were open circuited were located under the same face of the sliding block, the bridge was rewired as a single quarter bridge using one of the two intact elements in the other face. This arrangement endured without further failure for the remainder of the tests, i.e. from Tests 114 to 343 inclusive. Of course, with this arrangement data could only be obtained from the sliding block when it experienced load on the side containing the intact gauge element. At all other times the bridge would yield a null output.

It was believed that the cause of these failures was breakage of the lead wires from one side of the sliding block where they were exposed to movement of the mechanical components and the hydraulic oil within the hub.

### 6.4.3 Shaft Movement Probes

The poorest performance of any part of the instrumentation was experienced with the shaft movement probes. The forward starboard probe failed soon after the number seven ballast tank, in which the probe electronics were mounted, was flooded and before any data was obtained with the system.

The remaining three probes were connected into the data acquisition system on June 21 and all three gave good data for Tests 8 to 12 inclusive. Then the forward port probe and the aft port probe failed, during the period June 21 to June 30, so that on June 30, when testing was resumed, only the aft top probe was functional. The last probe continued to function throughout the remainder of the tests. During the shutdown in McKinley between June 21 and June 30 the number seven ballast tank was drained and entered to determine the cause of the failures. It was found that the junction box containing the original signal conditioning for the forward pair of probes had admitted water, which accounted for the failure of those two signals. The forward starboard probe amplifier was located lower in the junction box than the forward port one, which was evidently why it had failed first. The depth of water found in the junction box was approximately one to two inches. The water had probably leaked in through the split grommet cable glands. The signal cables leading from the junction box to the probes were found to be impregnated with salt water and it was the effect of the salt water on the cable impedance that was probably responsible for the loss of signal, as the electronics modules themselves were still functional.

The second junction box, which contained the electronics for the aft pair of probes was found to be dry and there was no evidence of salt water damage to either of the cables for those two probes. It was believed that the failure of the aft port probe was due to either breakage of, or salt water incursion into the section of the probe cable exposed to the sea water beneath the rope guard. The aft port probe cable was exposed for almost one meter of length beneath the rope guard compared with approximately a 25 cm length for the aft top probe. Both cables were supported by wire clamps to lugs on the outside of the seal housing, but due to assembly difficulties, the aft port probe cable could not be as well secured over all of its length as the aft top probe cable and was thus more vulnerable.

### 6.4.4 Shaft Thrust

The only other transducer failure experienced during the tests was first noted at Test 206. In this test it was observed that the shaft thrust signal was beginning to exhibit significant dc drift which became progressively worse throughout the remainder of the tests. It was likely that one of the strain gauges applied to the shaft to form the new thrust bridge was inadequately bonded. It was also observed that the newly applied thrust bridge exhibited the same once-per-revolution cycle output variation as the original bridge that it replaced. The cause of the variation was not understood since the bridge was one that should have been compensated for extraneous effects such as shaft bending strains.

All other transducers functioned according to specification throughout the tests, although the shaft RPM pulse train was intermittant for some of the early tests until suitable ac coupling components were installed to feed the signal to the data acquisition system.

### 6.4.5 Signal Conditioning and Data Acquisition

The strain gauge signal conditioning and slip ring assembly gave excellent performance. The total zero drift of the strain gauge bridges was less than 30 mv out of a 10 v range in the worst case over the duration of the tests. The total electrical noise level on the signals was typically 1 to 2 least significant bits of the A to D converter resolution (i.e. 5 to 10 mv out of a 10v range).

The analog-to-digital subsystem also gave excellent performance, as did the analog event detection circuitry and the HP 9836 computers. Of the 343 events recorded on floppy disk, only one (Test 120) was found later to be unreadable, and this was believed to be due to a defective diskette. During data analysis work with one of the HP 9836 computers, a memory parity check error was encountered on one occasion. This was found to have occurred in one of the Eventide Corp. One Megabyte memory boards installed in the unit and was corrected by performing a board swap and restarting the system.

True continuous scanning with buffer wraparound was not achieved in the HP 9836 due to a latency that occurred when the HP 9836 DMA Controller accessed the buffer pointers upon reaching the high-time end of the buffer. This latency caused one or more readings from the multi-programmer to be lost when wraparound occurred, leading to a loss of the scanning sequence in the input buffer. This problem was believed to be due to a hardware design error in the DMA controller and which has since been corrected in a product revision by the manufacturer. The problem was avoided by aborting the inbound data transfer from the multi-programmer when the HP 9836's data buffer became full and then resequencing and restarting the data input at the beginning of the buffer under software control. The process required that the input signals not be monitored for 5 milliseconds in each 40 second period. It was subsequently discovered that a software error, involving the setting of the buffer pointers when an event was detected and copied from memory to disk, occasionally resulted in the loss of a small amount of data at the end of the event (about 5 to 10 percent of the event duration).

# 7. ICE INTERACTION MODEL

## 7.1 Introduction

Work done to date on the ice/propeller interaction problem can be characterized as follows:

- Analytical Investigations: Open propellers milling very large blocks of immovable ice. Quasi-static state of interaction (no inertia loads and static ice strength properties only). See for example Reference 7.1.

- Experimental Investigations: Small scale ice propeller interaction experiments in air or water. Milling mode or single block impact mode. See Reference 7.2.

- Full Scale Investigations: Only some shaft thrust and torque data are available, which represents the integrated and filtered response of the system to ice loads. See Reference 7.1.

Since none of the above information sources could be applied directly to the problem at hand, it was decided to develop a new understanding based on first principles of the dynamic interaction between the CPP system of MV Robert LeMeur and ice blocks entering the nozzle.

The development of this new understanding and its analytical representation is the subject of this section. It should be emphasized that all of the models have sketchy, exploratory character. Comparison with actual field data will be reserved for later reports of this project. Only then will the final ice-propeller interaction model be developed.

The tools used for the model development are:

- Newton's Laws of Dynamics;
- Properties of ice as a material (ie elastic/plastic/brittle behaviour of ice);
- First principles of hydrostatics and hydrodynamics;
- Handbook formulas referenced in the text.

The models developed here are not referenced after those existing already since those do not reflect the particular nozzle-propeller-ice scenarios. The models are therefore evolved from "scratch" using the tools listed above.

## 7.2 General Characterization of Ice-propeller Interaction

There are 3 main parameters which affect the type of interaction between two colliding bodies:

Size of the bodies; Their strength, and; The energy they carry.

It is obvious that a low energy collision between two strong bodies will result in local damage only. Conversely, a high energy collision between two weak bodies may result in complete disintegration of both bodies. In the first case, the interaction is limited to the local contact zone and the bulk properties of the bodies (volume, shape, etc.) do not change significantly during the impact. In the second case, the whole body may be affected by the impact, and interaction parameters such as masses, geometries, etc., may be drastically changed during the interaction process.

In order to find out which type of interaction the shrouded propeller impacting an ice block represents, the following general procedure has been evolved.

Step One: The maximum energy which can be dissipated during plastic collision is:

$$KE = 2 * mV^2/2 \qquad [Nm]$$

This is because the propeller, rotating with the velocity (V) [m/s], can, in the worst case, accelerate the mass of ice (m) [kg] to that velocity. The multiplier of two represents an equal amount of energy being dissipated in the crushing of ice. If the propeller was stationary and the ice was moving with velocity (V), then the kinetic energy of the ice block would be $mV^2/2$. All of that energy would be dissipated in crushing of the ice as it impacts the blade. When the propeller is moving against stationary ice, not only does it crush the ice but it also accelerates the ice mass to the velocity (V). Thus, the propeller is loosing 2 times the kinetic energy of the ice at the exit and the ice absorbs one $mV^2/2$ in plastic deformation.

Step Two: When the kinetic energy of an impacting block of ice is divided by its volume, we arrive at the "specific crushing energy" absorbed by it:

$$p = mV^2/2\,\nabla = \rho V^2/2$$

Where $\nabla$ is the volume, [$m^3$], of the block. This ratio, having dimension of [Pa] represents the average "pressure" in the body due to the interaction. If this value, compared to the "strength" of ice (measured as crushing, or compressive strength, in [Pa]) is small, then it is likely that the iceblock will remain intact during the impact. If the value is large, then there are chances that the ice block will fail in a global fashion (shattering, cracking). Symbolically:

If $p \ll \sigma_{strength}$ then a 'local' type of interaction occurs, and;
If $p \geq \sigma_{strength}$ then a 'global' type of interaction takes place.

Step Three: The distinction between a 'local' and a 'global' type of interaction enables us to judge what determines the maximum load that can be developed during an impact. In the 'local' case, the maximum load is governed largely by the amount of energy being dissipated. Greater energy available for the interaction means higher penetration and higher (in general) loads. Ice will absorb this energy without 'global' collapse. In the 'global' case, ice will shatter before the blade reaches full penetration and so, the limit load is governed by the energy absorbtion ability of ice. Thus we have:

| Type of interaction | $p/\sigma_{strength}$ | Maximum load limited by |
|---|---|---|
| Local | small | energy of impact |
| Global | large | "strength" of ice |

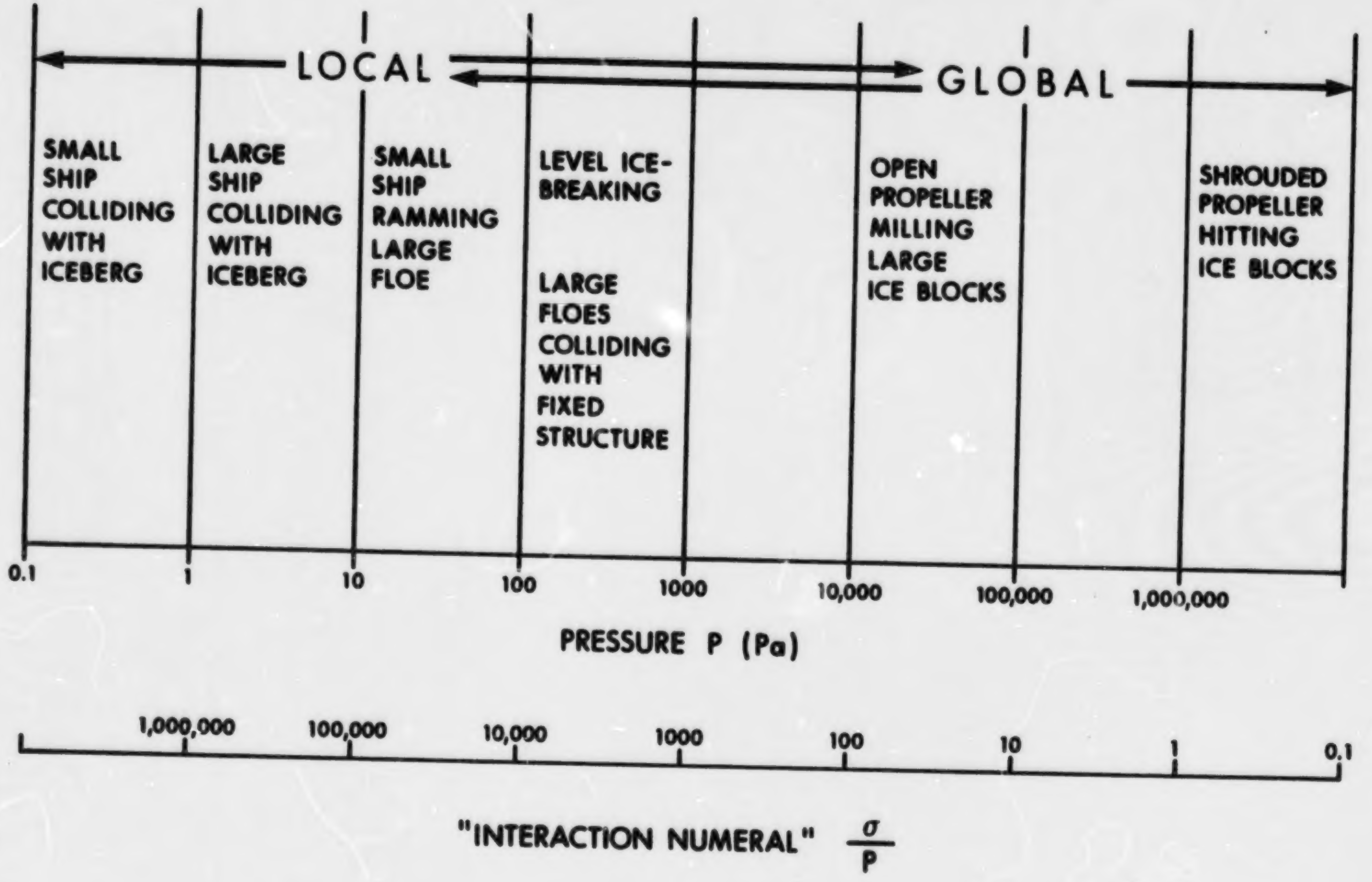
Coarse calculations performed for the several interaction scenarios are shown in Figure 7.2.1. They reveal that the propeller ice interaction is the most 'global' of all the interactions considered in the icebreaking business.

Further, very important distinctions between open propellers and shrouded propellers during ice/propeller interactions emerge:

> Limit load in open propeller interaction is governed by the energy available in the system, and;
> Limit load in a shrouded propeller interaction is governed by the energy absorbtion ability (strength) of ice.

ICE "STRENGTH" INDEX

$\sigma = 1$ MPa


LOCAL
GLOBAL
SMALL SHIP COLLIDING WITH ICEBERG
LARGE SHIP COLLIDING WITH ICEBERG
SMALL SHIP RAMMING LARGE FLOE
LEVEL ICE-BREAKING
LARGE FLOES COLLIDING WITH FIXED STRUCTURE
OPEN PROPELLER MILLING LARGE ICE BLOCKS
SHROUDED PROPELLER HITTING ICE BLOCKS
0.1
1
10
100
1000
10,000
100,000
1,000,000
PRESSURE P (Pa)
1,000,000
100,000
10,000
1000
100
10
1
0.1
"INTERACTION NUMERAL" $\frac{\sigma}{P}$

| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER<br>INTERACTION PARAMETERS | TITLE:<br>TYPES OF INTERACTIONS |
|---|---|---|
| | | FIGURE No. 7·2·1 |

Such a distinction may have several design implications. This study deals with a 'global' ice interaction phenomenon.

## 7.3 Geometry of Interaction

### 7.3.1 Geometry of Ice

The size of the ice pieces entering the nozzle is bounded by the shroud's inner surface and the shaftline.

The maximum cross sectional area of a rectangular ice block which could enter the nozzle is calculated as follows (see Figure 7.3.1 for notations):

$$b = 2\,R_o \sin\alpha$$

$$h = R_o \cos\alpha - r_o$$

$$bh = A_{\otimes} = R_o^2 * (\sin 2\alpha - 2r_o/R_o \sin\alpha)$$

Condition for the extremum is:

$\partial A_{\otimes}/\partial\alpha = 0$ which gives

$$\cos\alpha = (r_o/R_o + ((r_o/R_o)^2 + 8)^{1/2})/4$$

Using MV Robert LeMeur data, we obtain:

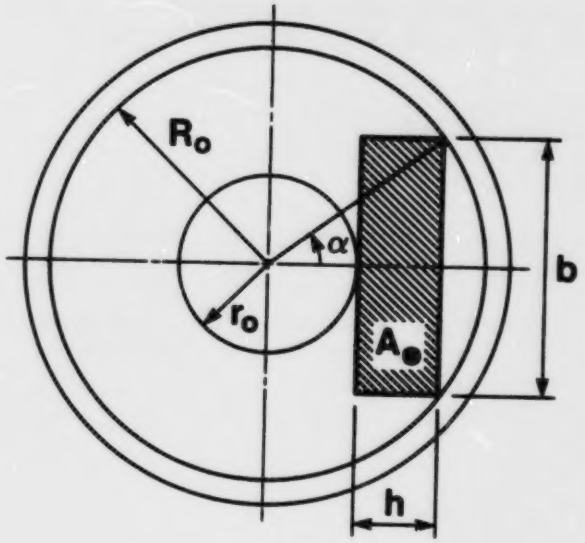
$$\alpha = 36.4^o \text{ and}$$
$$(A_{\otimes})_{max} = 1.171\ m^2$$

If the ice block is not of a rectangular shape, a somewhat larger size could be accommodated. For a triangular shape, we obtain:

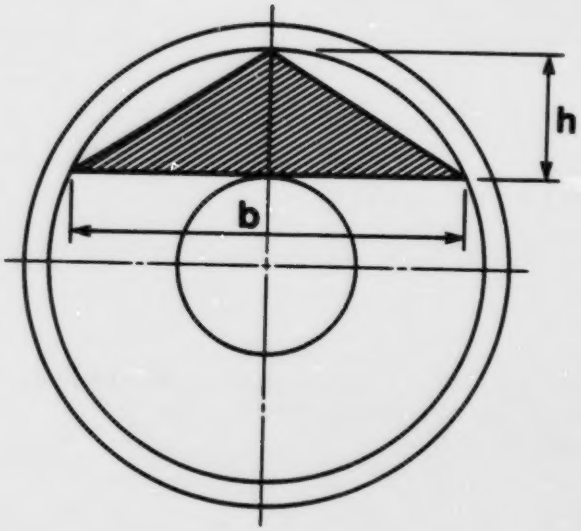
$$(A_{\otimes})_{max} = 1.32\ m^2$$

Lengthwise, the ice block can extend for several meters. However, the most likely shape of the piece is triangular, and its initial positions in the ring are shown in Figure 7.3.2.

The most probable position of ice blocks in the nozzle is the upper half of the ring as ice is sucked from the sides and the bottom of the ice island.



$b_{max}$ = 1.78 m
$h_{max}$ = 0.657 m
$A_{e\,max}$ = 1.17 $m^2$



$h_{max}$ = 0.95 m
$b_{max}$ = 2.79 m
$A_{e\,max}$ = 1.32 $m^2$

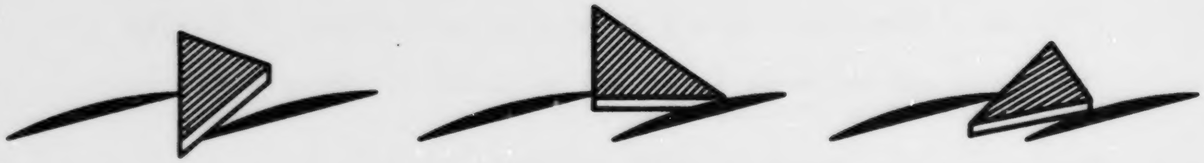
**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

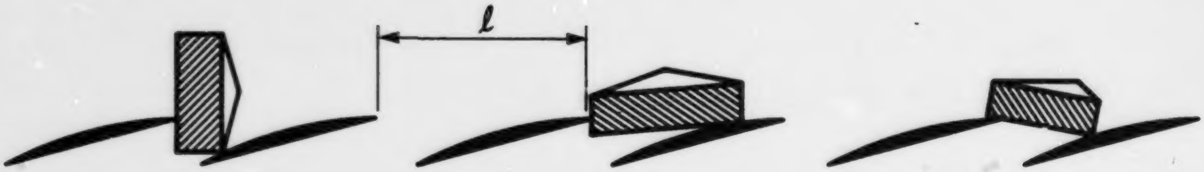
TITLE:
**MAXIMUM BLOCK SIZE DEFINITION**

FIGURE No. 7·3·1

## PLAN VIEW

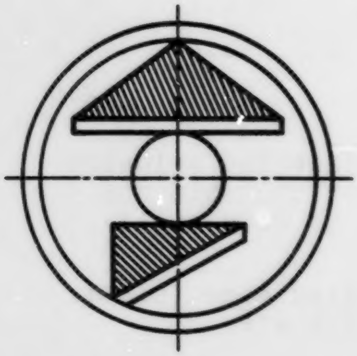


HORIZONTAL

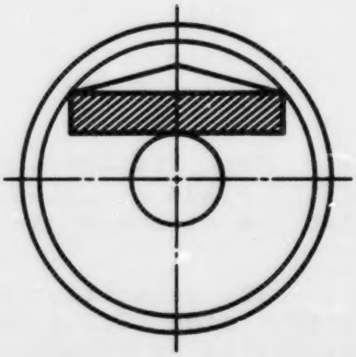


VERTICAL

## ELEVATION LOOKING FORWARD



VERTICAL



HORIZONTAL

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE: POSSIBLE ICE BLOCK<br>INITIAL IMPACT POSITIONS<br>FIGURE No. 7·3·2 |

### 7.3.2 Geometry of Rotating Propeller

Table 7.3.1 summarizes propeller blade geometry. Circumferential spacing between the blades is calculated as:

$d = 2\pi Rr/(RZ)$, where Z denotes the number of blades.

The blade advancement in an earth-fixed coordinate system is calculated as follows:

Time to turn a blade through an angle $2\pi/Z$ is

$$t_{bl} = 2*R/(Z*2\pi*Rn) = 1/(Z*n)$$ , where n is RPS;

Axial advancement of the blade is then:

$s=V_{ship} * t_{bl}=V_{ship}/(Z*n)$, ($s=0.3$ m for $V_{ship}=4$ m/s);

The angle of advancement $\varphi_1$, is defined as

$$\tan\varphi_1 = s_{axial}/s_{circum} = V_{ship}/*Dn;$$

The velocity of the blade in fixed coordinate system is:

$$V_{blade} = (V^2{}_{ship} + (2*\pi rn)^2)\theta.^{2} \qquad ^{1/2}$$

Calculated values for the tip of MV Robert LeMeur propeller are:

| $V_{ship}$ | [m/s] | 0 | 2 | 4 | 6 | 8 |
|---|---|---|---|---|---|---|
| $V_{blade}$ | [m/s] | 32.8 | 32.9 | 33.1 | 33.4 | 33.6 |
| $\varphi_1$ | [°] | 0 | 3.5 | 6.9 | 10.3 | 12.0 |

From the above table it is evident that the velocity of the blade is insensitive to the speed of the ship and that the attack angle $\varphi_1$ of the blade tip is very small.

The velocities of attack of the leading edge (L.E.), suction side (S.S.) and pressure side (P.S.) are calculated as follows (see Figure 7.3-3).

$$V_{L.E.} = V_{blade}*\cos(\theta_r - \varphi_r)$$

$$V_{S.S.} = 0 \text{ (always for } \varphi_r < \theta_r)$$

$$V_{P.S.} = V_{bl}*\sin(\theta_r - \varphi_r)$$

| r/R | PITCH | PITCH RATIO | PITCH ANGLE | DISTANCE BETWEEN BLADES | LENGTH OF BLADE SECTION |
|---|---|---|---|---|---|
| [-] | [mm] | [-] | [°] | [mm] | [mm] |
| 1.0 | 4121 | 0.437 | 23.6° | 2356 | 1242 |
| 0.975 | 4090 | 0.445 | 24.0° | 2300 | 1291 |
| 0.950 | 4059 | 0.453 | 24.4° | 2238 | 1340 |
| 0.90 | 3992 | 0.470 | 25.2° | 2120 | 1380 |
| 0.85 | 3924 | 0.490 | 26.1° | 2003 | 1370 |
| 0.80 | 3853 | 0.511 | 27.1° | 1885 | 1360 |
| 0.7 | 3708 | 0.562 | 29.3° | 1649 | 1200 |
| 0.6 | 3549 | 0.628 | 32.1° | 1414 | 1050 |
| 0.5 | 3305 | 0.701 | 35.0° | 1178 | 882 |
| 0.4 | 3216 | 0.853 | 40.5° | 942 | 714 |
| 0.375 | 3130 | 0.886 | 41.5° | 883 | 670 |

Prop Dia.   3.000 m
Nozzle Dia. 3.030 m
Number of blades:  4.

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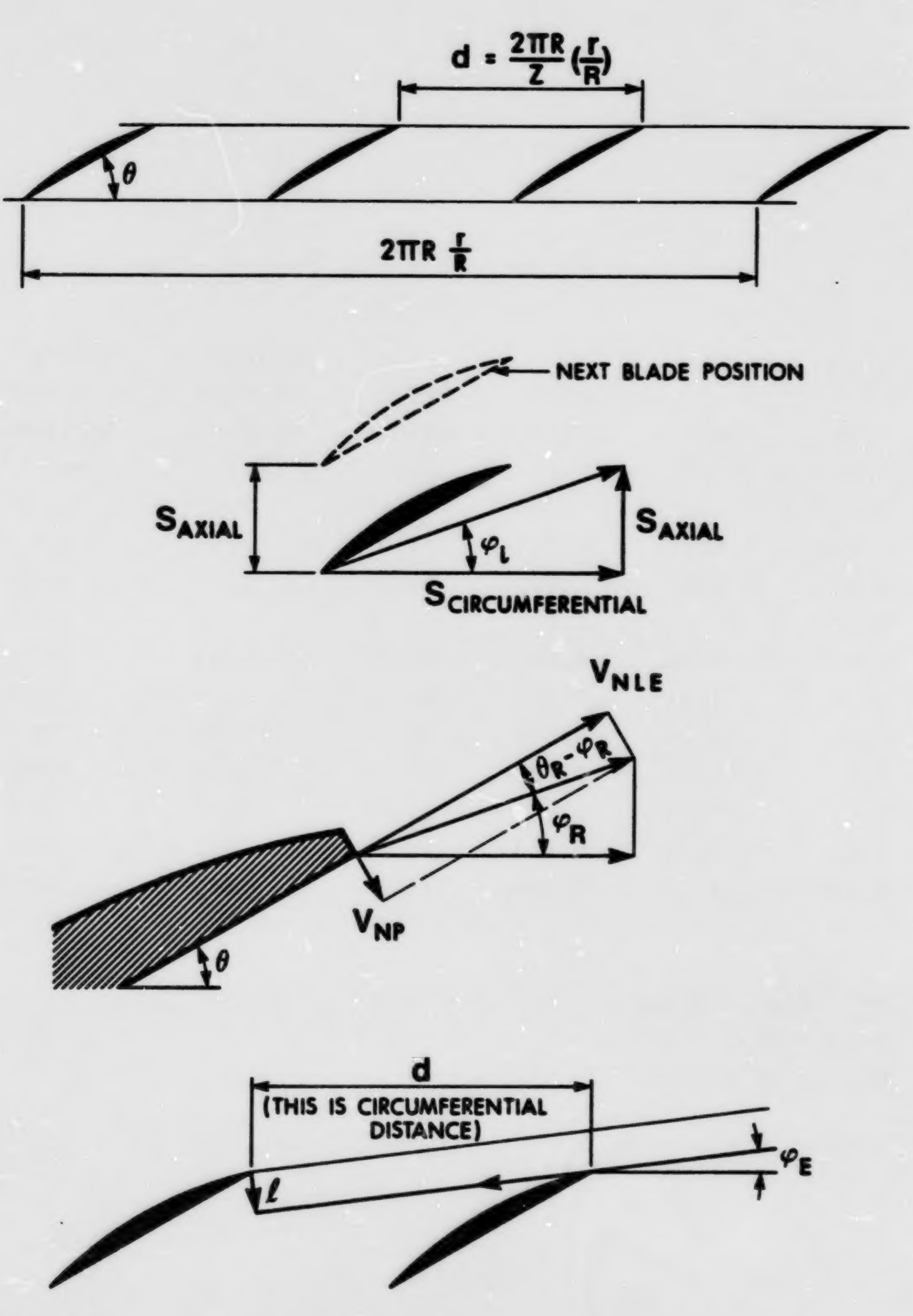
MEASUREMENT OF ICE PROPELLER
INTERACTION PARAMETERS

TITLE:
PROPELLER BLADE GEOMETRY
SUMMARY

TABLE 7.3.1


d = 2πR/Z (r/R)
θ
2πR r/R
NEXT BLADE POSITION
S AXIAL
φ l
S AXIAL
S CIRCUMFERENTIAL
V NLE
θR - φR
φR
V NP
θ
d
(THIS IS CIRCUMFERENTIAL DISTANCE)
ℓ
φE

CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE
PROPELLER INTERACTION
PARAMETERS

TITLE: BLADE VELOCITY
DEFINITIONS

FIGURE No. 7.3.3

Where $\Theta_r - \varphi_r$ is the angular difference between the pitch angle and the velocity of the blade or "angle of attack".

| r/R | $V_{ship}$ [m/s] | $V_{blade}$ [m/s] | $\varphi_r$ [o] | $\Theta_r$ [o] | $V_{S.S}$ [m/s] | $V_{L.E.}$ [m/s] | $V_{P.S.}$ [m/s] |
|---|---|---|---|---|---|---|---|
| 0.4 | 2 | 13.3 | 8.6 | 40.5 | - | 11.3 | 7.0 |
| 0.6 | 2 | 20.0 | 5.8 | 32.1 | - | 17.9 | 8.9 |
| 0.8 | 2 | 26.3 | 4.4 | 27.1 | - | 24.2 | 10.1 |
| 1.0 | 2 | 32.6 | 3.5 | 23.6 | - | 30.6 | 11.2 |

Note that near the tip of the blade, the velocity of the pressure surface is much lower than that of the leading edge.

### 7.3.3 Other Critical Scenarios

When the angle between the velocity vector of the incoming ice and the propeller disc is $\varphi_E$, then the maximum width of the ice piece being 'shaved-off' is:

$\ell \approx d \sin \varphi_E$ (see Figure 7.5.5 for illustration)

For MV Robert LeMeur propeller, we have:

|  |  | VALUES OF $\varphi_E$ |  |  |
|---|---|---|---|---|
| r/R | d | 0° | 10° | 20° |
|  |  | VALUES OF $\ell$ |  |  |
| 0.6 | 1.4 | 0 | 0.24 | 0.48 |
| 0.8 | 1.9 | 0 | 0.33 | 0.65 |
| 1.0 | 2.35 | 0 | 0.40 | 0.80 |

### 7.3.4 Geometry of Water Inflow

The water inflow velocity influences the ice blocks' velocity of impact. The water velocity in the nozzle has three components:

- Axial
- Tangenetial
- Radial

Of these, the radial component is insignificant.

Axial velocity is computed as follows:

Assuming that the propeller is an 'ideal' one, i.e. does not have any losses, the axial velocity in the disk area can be computed from (Reference ):

$$V_{mp} = V_{ship} (1 + (1 + C_T)^{1/2})/2 \text{ where:}$$

$$C_T = \text{Thrust} / (1/2\ \rho * V^2_{ship} * A_{prop})$$

Computations of $V_{mp}$ are performed in the table below:

| | | | | | | |
|---|---|---|---|---|---|---|
| $V_{ship}$ | [m/s] | 0 | 2 | 4 | 6 | 7 |
| Thrust | [MN] | 0.63** | 0.52 | 0.43 | 0.34 | 0.29 |
| $V_{mp}$ | [m/s] | 6.5 | 7.0 | 7.7 | 8.6 | 9.1 |

** This value can be compared with the thrust of the ideal propeller given by:

$T_{id.prop} = (2\rho AHP^2)^{1/3} = 955\ (HP * D)^{2/3}$ at the bollard condition.

In order to calculate the circumferential velocity (Vu) we will use Netherlands Ship Model Basin (NSMB) measured data for a similar ship:

| r/R | ωr [m/s] | Vu [m/s] | Vu/ωr [-] |
|---|---|---|---|
| 0.4 | 15.4 | 1.57 | .10 |
| 0.6 | 23.12 | 2.25 | .07 |
| 0.8 | 30.83 | 1.70 | .05 |
| 1.0 | 38.50 | 0.89 | .02 |

NOTE:
ωr denotes rotation speed of the blade

Ratios of Vu/ωr will be used for MV Robert LeMeur calculations, which are given in the table below:

| | | $V_{ship}$ | | 0 m/s | | | 6 m/s | |
|---|---|---|---|---|---|---|---|---|
| [r/R | ωr] [m/s] | Vu [m/s] | $V_{mp}$ [m/s] | $V_{tot}$ [ma] | $\varphi_E$ [°] | $V_{mp}$ [m/s] | $V_{tot}$ [m/s] | $\varphi_E$ [°] |
| 0.4 | 13.1 | 1.31 | 6.5 | 13.5 | 28.7 | 8.6 | 14.6 | 36.1 |
| 0.6 | 19.7 | 1.91 | 6.5 | 18.0 | 21.2 | 8.6 | 19.7 | 25.9 |
| 0.8 | 26.3 | 1.31 | 6.5 | 25.8 | 14.6 | 8.6 | 26.4 | 19.5 |
| 1.0 | 32.8 | 0.66 | 6.5 | 32.8 | 11.4 | 8.6 | 33.3 | 15.0 |

Geometry of the water inflow is shown in Figure 7.3.4.

## 7.4 Water Loads

### 7.4.1 Acceleration

Any solid body immersed in an accelerating fluid flow will experience a force due to the pressure differential between the two ends of the body (see Figure 7.4.1):

$$F=A_{\otimes}\ \Delta p=1/2\ \rho_W\ (V_1^2 - V_2^2)\ x\ A_{\otimes}=m_{body}\ (V_2^2 - V_2^2)\rho_W/\rho_B)/2l_B$$

Where $A_{\otimes}$ is the cross section of the body and $l_B$ its length.

Thus the body moves faster than the water flow if it is lighter than water, and slower if it is heavier.

Taking $V_1 \approx V_{mp}$ and $V_2 = 0.71\ V_{mp}$, we will have:

$$F/A_{\otimes} = \rho\ V_{mp}^2/4$$

For the MV Robert LeMeur:

| | | | | | |
|---|---|---|---|---|---|
| $V_{ship}$ | [m/s] | 0 | 2 | 4 | 6 |
| $F/_{A=1m^2}$ | [t/m$^2$] | 1.1 | 1.2 | 1.5 | 1.9 |

Thus, a piece of ice having a length of approximately 1m and a cross-section of 1m$^2$ will experience an accelerating force of one to two tonnes.

When an ice piece is stopped by the propeller blades this force remains a driving force pushing the ice against the blades.

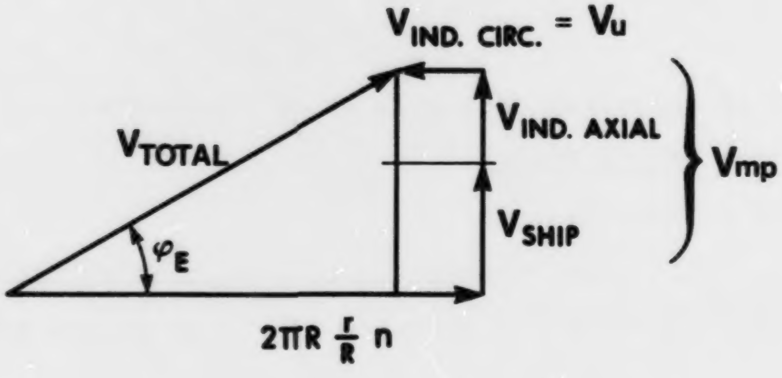
### 7.4.2 Buoyancy

A net force acting on an ice piece is:

$$F_B = (\rho_W/\rho_i - 1) * \text{Weight of Ice}$$

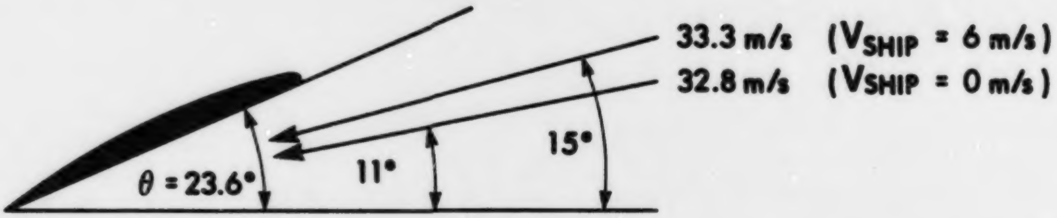
For an ice block of 1.1 m$^3$, weighing 1 tonne, the net force is

$$F_B = 0.1 \text{ tonne}$$

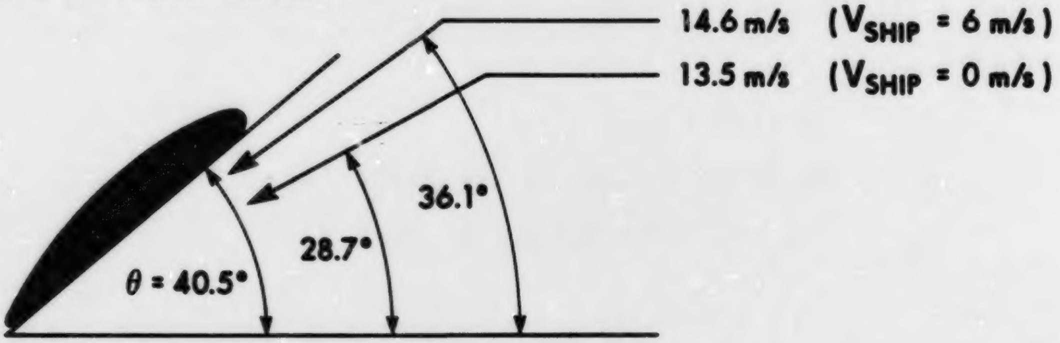

$V_{IND.\ CIRC.} = V_u$
$V_{TOTAL}$
$V_{IND.\ AXIAL}$
$V_{mp}$
$V_{SHIP}$
$\varphi_E$
$2\pi R \frac{r}{R} n$

$$\tan \varphi_E = \frac{V_{SHIP} + V_{IND.\ AXIAL}}{2\pi R \frac{r}{R} n - V_{IND.\ CIRC.}}$$

TIP VELOCITIES


33.3 m/s ($V_{SHIP}$ = 6 m/s)
32.8 m/s ($V_{SHIP}$ = 0 m/s)
15°
11°
$\theta$ = 23.6°

ROOT VELOCITIES


14.6 m/s ($V_{SHIP}$ = 6 m/s)
13.5 m/s ($V_{SHIP}$ = 0 m/s)
36.1°
28.7°
$\theta$ = 40.5°

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**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

TITLE: **GEOMETRY OF WATER INFLOW**

FIGURE No. 7·3·4

Consequently, the buoyancy of ice is not considered to be significant during ice-propeller interaction.

### 7.4.3 Centrifugal

When a fixed body is located in a rotating liquid it is the subject of the pressure differential in the liquid, resulting in a radially oriented force (see Figure 7.4.1).

For the MV Robert LeMeur and $0.8 < r/R < 1.0$ we have:

$$\Delta p = \frac{1}{2} \rho \, (-1.31^2 + 0.66^2) = -0.6 \text{ kPa, and}$$

for the $0.4 < r/R < 0.6$;

$$\Delta p = \frac{1}{2} \rho \, (-1.31^2 + 1.91^2) = -0.9 \text{ kPa}$$

Thus, a force acting on the 1 $m^3$ ice block is:

$F \approx 600$ N near tip of the prop.
$F \approx 900$ N near the root.

These forces are comparable with the buoyancy forces.

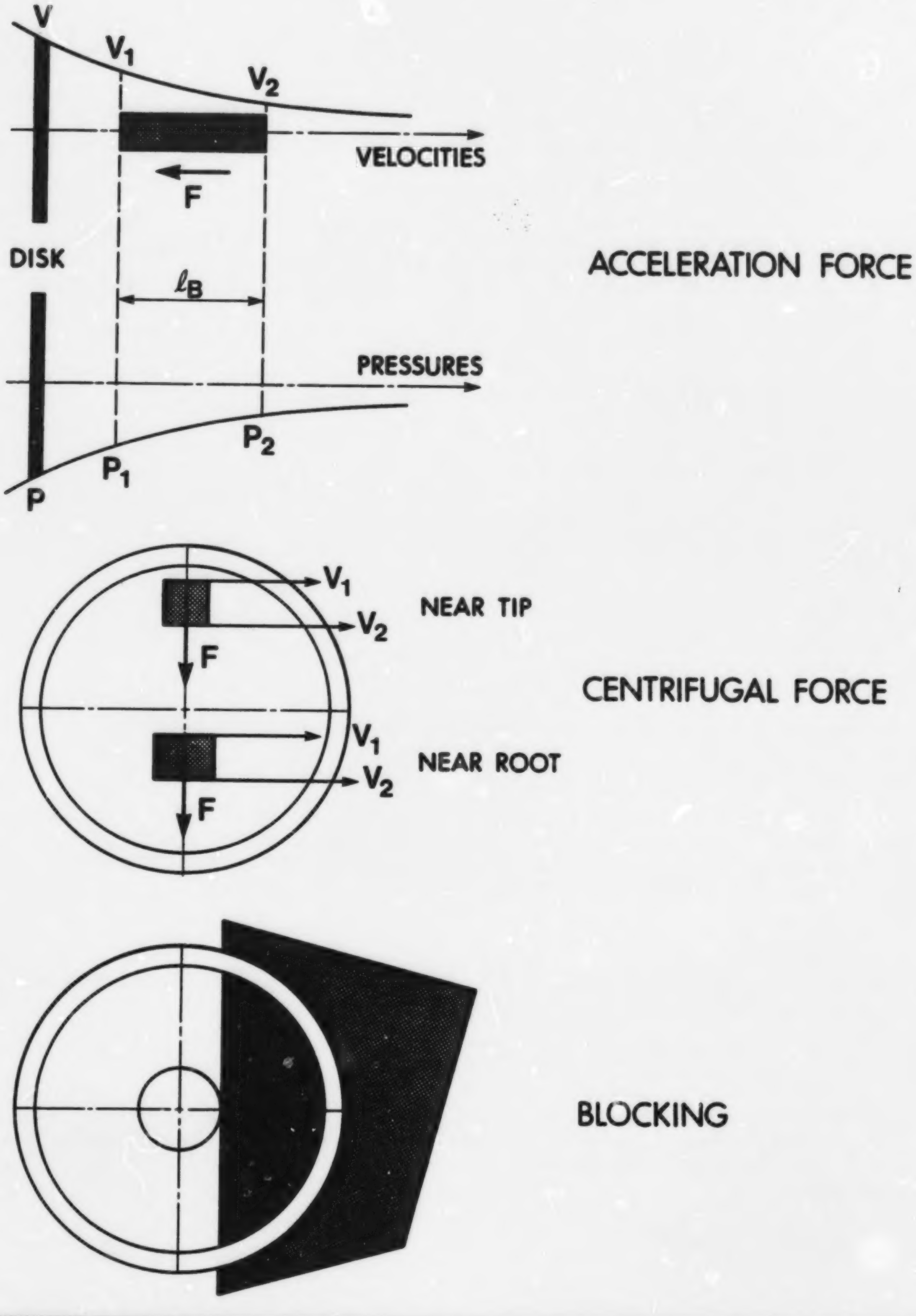
When an ice piece is rotating with the speed $\omega$, the centrifugal force is $m\omega^2R$. For the MV Robert LeMeur this force is approximately 72 tonnes per 1 tonne of ice, therefore, the ice block is quickly driven against the nozzle's inner ring.

### 7.4.4 Drag

Reynold's number (Re) for an ice piece being pushed by the blade at approximately 30 m/s is:

$$Re \approx V*(\ell = 0.5 \text{ m})/\upsilon = 8.4*10^6$$

This defines the flow as supercritical (turbulent). Drag coefficient for such a flow past the ice in the shape of a cube is approximately 2.


V
V1
V2
VELOCITIES
F
DISK
ℓB
PRESSURES
P2
P1
P
ACCELERATION FORCE
V1
NEAR TIP
V2
F
CENTRIFUGAL FORCE
V1
NEAR ROOT
V2
F
BLOCKING

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**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** HYDRODYNAMIC LOADS DEFINITION

**FIGURE No.** 7·4·1

Drag is then calculated as:

$$R = C_R \, ½ \, \rho \, V^2 \, A_{\otimes} = 1000 \, V^2 A_{\otimes}$$

This means that 1 $m^2$ surface at $V = 30$ m/s, has a resistance $R = 90$ tonnes, which translates into 0.9 MPa pressure on the contact surface of the pushing blade.

For the same 1$m^2$ of ice surface, and ice being forced against the axial flow against the blade:

$$R = 2 * ½ * 1000 * 7^2 = 4.9 \text{ tonnes/m}^2$$

Thus drag forces are a very significant component of ice-blade interaction.

### 7.4.5 Shadowing

Hydrodynamic load on a blade due to the thrust development is of the order of 6 tonnes per blade in unobstructed flow. When the blade passes near the ice block, which 'sits' on the nozzle's top surface, flow is disturbed and a 'shadow' effect is created. See Figure 7.4.2 for the illustration and definition of symbols.

If the speed of the blade is high, then a cavity may form on the suction side. Assuming the pressure side experiences dynamic pressure:

$P_{pressure} = \rho(V\sin\Theta)^2$, and the suction pressure is:

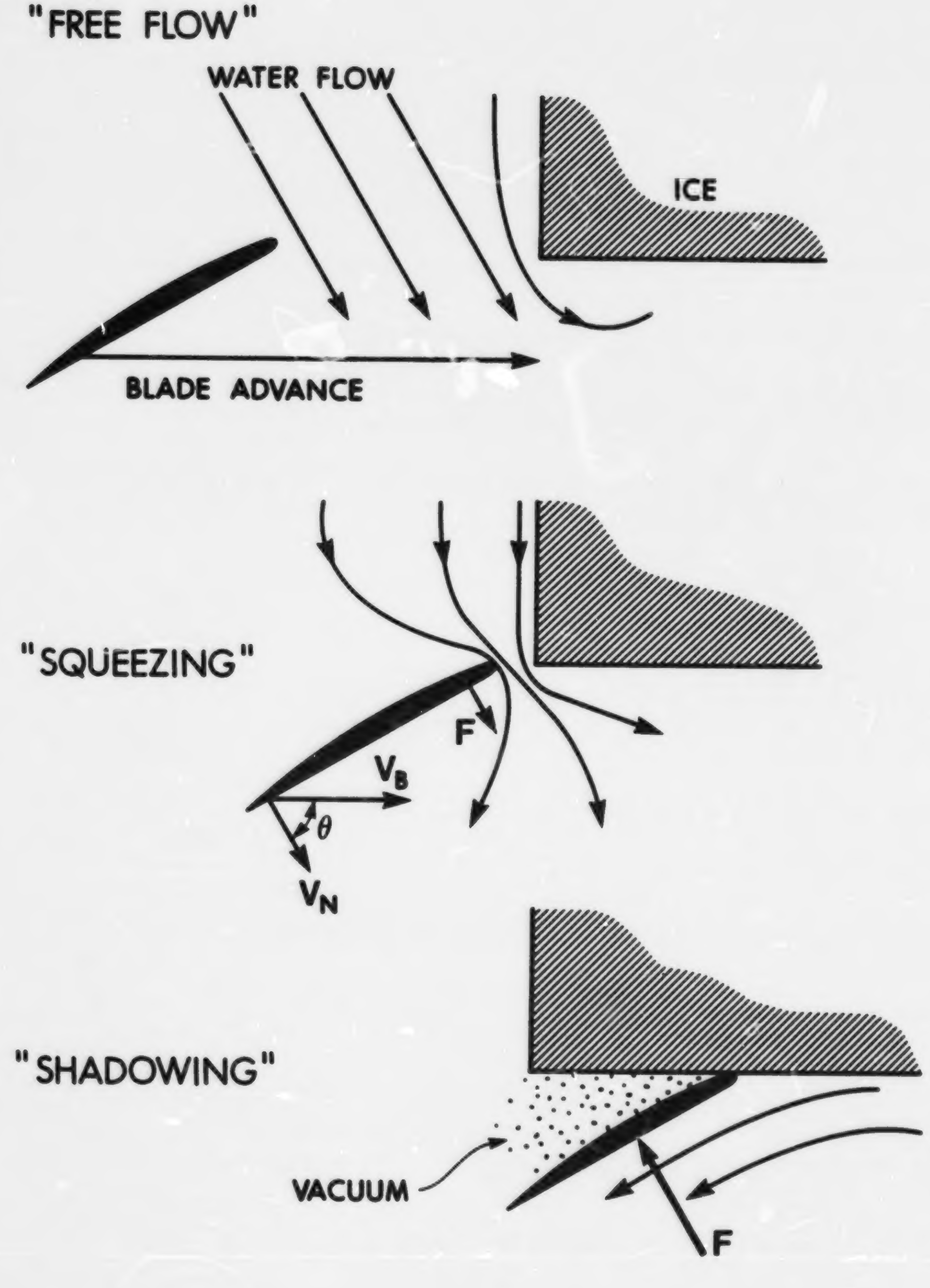
$P_{suction} = P_{cav} = 800$ Pa. ($P_{cav}$ denotes the cavitation pressure).

The load on the blade, due to this effect, becomes:

$$F = \Delta p * A_{blade} = A_{blade} \, (\rho V^2 \sin^2\Theta + \gamma H + p_o - P_{cav})$$

$$F = A_{blade} \, (\rho V^2 \sin^2\Theta + \gamma H + 0.1 \text{ kPa}),$$

($p_o$ is the atmospheric pressure)


"FREE FLOW"
WATER FLOW
ICE
BLADE ADVANCE
"SQUEEZING"
F
$V_B$
$\theta$
$V_N$
"SHADOWING"
VACUUM
F

CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE
PROPELLER INTERACTION
PARAMETERS

TITLE:
SHADOWING EFFECT

FIGURE No. 7·4·2

for the M V Robert LeMeur's blade tip:

$V \cong 30$ m/s
$H = 1$ m
$\theta = 22^{o}$
$F/A_{blade} = 0.136$ MPa

As the upper half of the blade has an area of approximately 0.7 $m^2$, the maximum anticipated load due to the shadowing effect is $F_{max} = 9.5$ tonnes, which is more than hydrodynamic (bollard) thrust. Direction of the load is forward. Thus, a large load can be developed on the blade even without ice-blade contact (load being the difference between the steady-state hydrodynamic force and shadowing force).

### 7.4.6 Added Mass

The accelerating of an ice piece of a "thin" rectangular shape requires overcoming the "added" mass. The coefficient of added mass for such a form is $\lambda = ½$. Thus:

$F = m(1 + ½)a = 1.5\ m*a$, where a denotes acceleration

### 7.4.7. Blocking

Blocking may occur when an ice piece of sufficiently large area rests on the mouth of the nozzle. The maximum area blocked by the straight edge (see Figure 7.4.1) is 27% of the total nozzle area.

Blocking has two effects:

It increases drag (slows down the ship), and;
It diminishes water inflow into the nozzle, which results in the loss of thrust, propeller over-speeding and large load fluctuations on the blades.

The overall loss of thrust of the propeller is estimated to be in direct proportion to the blocked area.

For $V_{ship} = 4$ m/s, drag force due to the blocking is calculated to be:

## SUMMARY OF WATER INDUCED LOADS

| | NATURE OF THE LOAD | POINT OF APPLICATION | DIRECTION | MAGNITUDE (TONNES) | COMMENTS |
|---|---|---|---|---|---|
| 1 | Flow Acceleration | prop blade suction side | axial aft | 1 to 2 | When block is stopped |
| 2 | Buoyancy | nozzle's inner ring top | upwards | ~ 0.1 | Too small to consider |
| 3 | Centrifugal due to liquid | nozzle's inner ring | circumferential | ~ 0.09 | Too small to consider |
| 4 | Centrifugal due to blade | blade leading edge | circumferential | ~ 72 | Not accounted for as ice will crack before reaching the full circumferential velocity |
| 5 | Drag axial | blade suction side | axial | 5 | To be included |
| 6 | Drag circumferential | blade leading edge | circumferential | 90 | See comment 4 |
| 7 | Shadowing | blade | out-of-plane | 10 | To be included |
| 8 | Added mass | blade | same as that of ice block | 0.5 | To be included |
| 9 | Blocking | nozzle ring and propeller blade | axial | 3 | To be included |

$R = \rho * 1/2 * 2 * 4^2 * 0.27 * \pi * 3^2/4 \approx 3$ tonnes,

which is a small fraction of the thrust.

However, the change of the load on one blade due to the blockage may be of significance.

A summary of water induced loads is given on the next page.

## 7.5 Ice/Blade Interaction Models

### 7.5.1 Elastic Impact

Outside of the crushing zone, ice is an elastic material. The elastic properties of ice determine the pressure between the impacting body and ice, as the elasticity is the only link between action forces (crushing) and reaction forces (inertia). See Figure 7.5.1 for definitions.

Take an ice block represented by the spring of stiffness (k, [N/m] and the mass (m), concentrated, for simplicity's sake, in the middle of it.

We will impact that spring with a flat plate representing the propeller blade. Since k of metal (in a local sense) >> k of ice, we will treat the blade as a rigid body.

Compression of the spring is $V_o t - X_G$
Force of the spring compression is $(V_o t - X_G)*k$

The equation of motion becomes:

$$\ddot{X}_G + \omega^2 X_G = \omega^2 V_o t \text{ where } \omega^2 = k/m$$

(We ignore the damping and other secondary effects.)

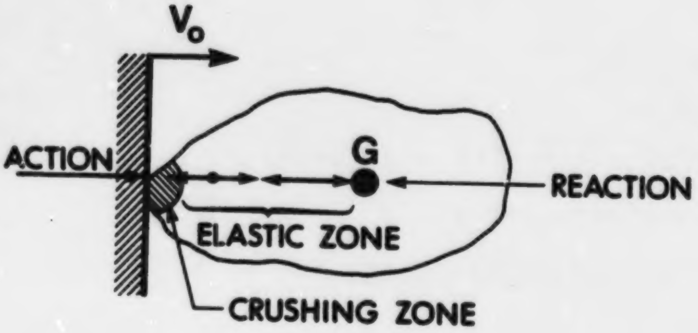
Solutions of this equation are:

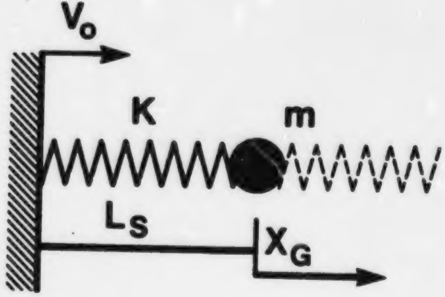
Displacement $X_G = V_o t - V_o t \sin\omega t/\omega t$

Velocity $\dot{X}_G = V = V_o*(+1 - \cos\omega t)$

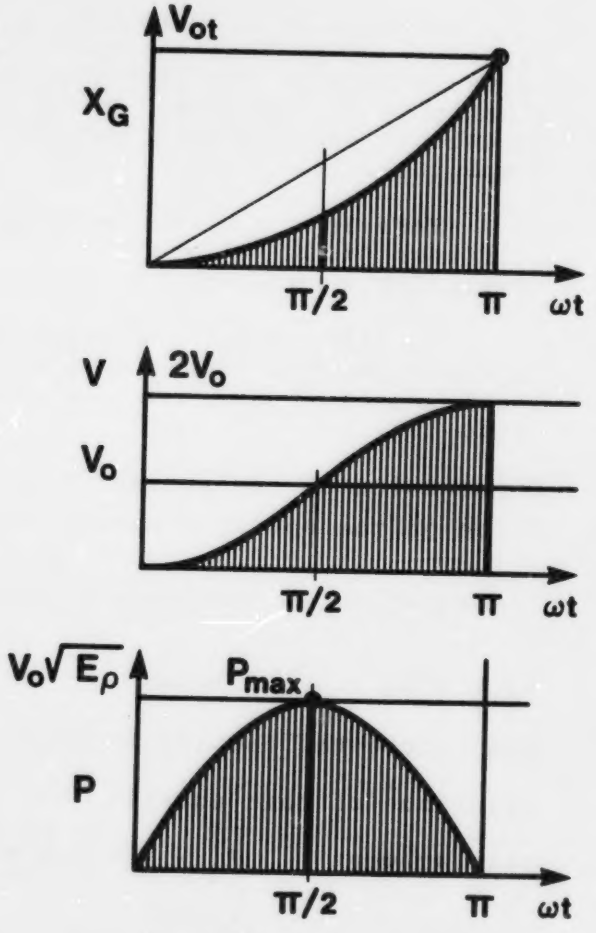
Acceleration $\ddot{X}_G = V_o \omega \sin\omega t$

Force $F = mV_o \omega \sin\omega t$


Vo
ACTION
G
REACTION
ELASTIC ZONE
CRUSHING ZONE



SIMPLIFIED MODEL



INTERACTION PARAMETERS

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE:<br>ELASTIC IMPACT |
| | | FIGURE No. 7·5·1 |

Maximum Force $F_{max} = V_o*(km)^{1/2}$

Duration of impact $T_{max} = \pi(m/k)^{1/2}$

Impact pressure $F/A = mV_o\omega\sin\omega t/A$

$P_{max} = mV_o\omega/A$, which, after substituting for m and k:

$m = L*A*\rho$,

$k = EA/L$, we obtain:

$$P_{max} = V_o*(E\rho)^{1/2}$$

Total energy absorbed at $T_{max}$ is

$$E_{total} = 2\ mV_o^2.$$

This is 4 times the initial kinetic energy and is due to the fact that at the $T_{max}$, no strain energy is stored in ice, and the velocity of it is twice $V_o$. It is completely analogous to a stationary ball being hit by some advancing plane ("racket") and bouncing off it with the velocity twice the velocity of the plane.

In comparison, for the perfectly plastic collision:

$E_{total} = mV_o^2$ (see the next paragraph)

This is one half the elastic value but twice as much as the initial kinetic energy of impact.

Some important conclusions can be derived from this simple model:

1. Force behaves cyclically (sine wave) during a collision.

2. Maximum force is directly proportional to the impact velocity, contact area and square root of $(E*\rho)$, i.e.:

$$F_{max} = V_oA*(E\rho)^{1/2}$$

For E** = $4*10^9$ Pa, $\rho = 1.5 * 900$ kg/$m^3$ and A = 1 $m^2$

$F_{max} = V_o * 2.3*10^6 N$

Maximum contact pressure in this case is therefore:

$p_{max} = V_o * 2.3$ MPa

For $V_o \approx 30$ m/s $p_{max} \approx 69$ MPa

This value is an order of magnitude higher than the value commonly used for pressure.

3. Contact pressure is proportional to velocity.

4. Duration of impact is not dependent on velocity but on the length of the ice piece ($L_s$):

$T_{max} = \pi L_s/c_o$ where $c_o = (E/\rho)^{1/2}$

5. The difference between ice loads given by this model and the 'plastic' one is:

$F_{elastic} = \rho A\ V_o\ c_o$, $F_{plastic} = \rho A\ V_o * V_o$ (mass transfer)
$F_{elastic}/F_{plastic} = c_o/V_o \sim 100:1$

Limitations of this model are:

- The complete lack of data on the high velocity impact pressures;
- The interaction numeral is very low, which stipulates that the ice piece would fall apart before mobilizing its elastic strength, and;
- The crushing zone of ice effectively 'cushions' the impact.

### 7.5.2 Plastic Impact

This model assumes that the energy of impact is dissipated through crushing at the contact zone. The value of crushing 'pressure', commonly assumed to be three times higher than the uniaxial compressive strength of ice, is considered to be constant throughout the interaction. Geometry of the model is shown in Figure

---

** See Paragraph 7.7 for the definition of ice properties

7.5.2. The mass of the propeller and propulsion train is assumed to be very much larger than that of the ice. The propeller's leading edge is approximated by the wedge of half of the entrance angle $\alpha$.

Equations of motion of ice block are:

$m\ddot{x}_G = F$ (linear motion)

$J_G\ddot{\varphi} = Fe$ (rotational motion)

$J_G = m\,(b^2 + d^2)/12$ (polar moment of inertia)

Denoting $u = 1 + 12e^2/(b^2 + d^2)$,

We will find that the kinetic energy acquired by the ice block is:

$$KE = m\,V_A{}^2 * 1/u$$

Solutions of these equations are:

$$X_G = V_o\,(\omega t - \sin\omega t)/u\omega$$

$$\dot{X}_G = V_o\,(1 - \cos\omega t)/u$$

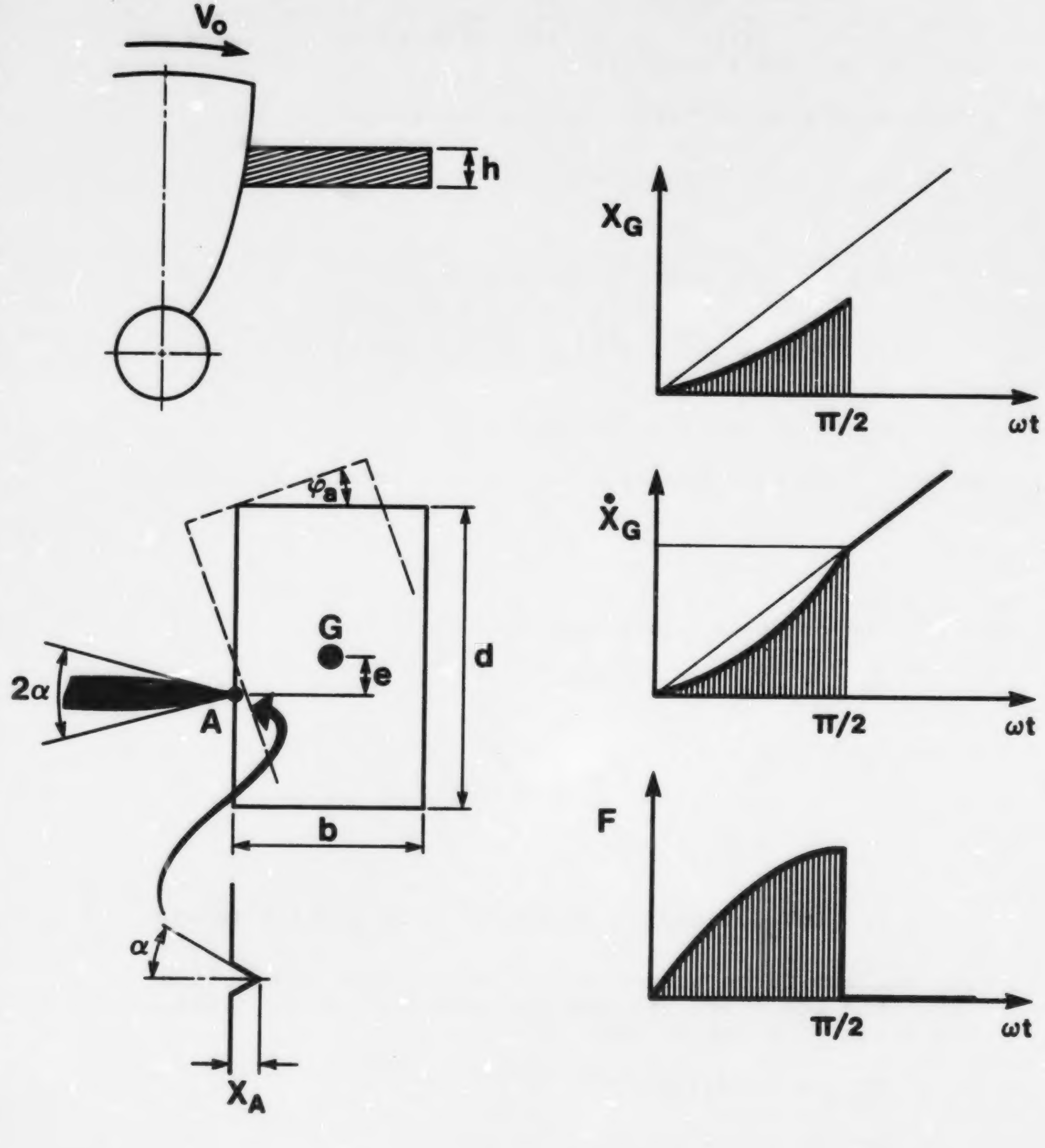
$$\ddot{X}_G = \omega\,V_o * \sin\omega t/u$$

$F = (mV_o\,\omega\sin\omega t)/u$ where, $\omega^2 = 2\sigma_{cr} * h * u\tan\alpha/m$,

The maximum force occurs at the end of the interaction (when the ice piece reaches the velocity of the blade at the point of contact) and its value is:

$$F_{max} = (m\omega V_o)/u$$

Which, fully expanded, gives:


V₀
h
X_G
π/2
ωt
φ_a
Ẋ_G
π/2
ωt
G
d
e
2α
A
b
F
π/2
ωt
α
X_A

CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE
PROPELLER INTERACTION
PARAMETERS

TITLE:
PLASTIC MODEL

FIGURE No. 7·5·2

$$F_{max} = (\rho bdh^2\sigma_{cr})^{1/2} * (2\ V_o^2 \tan \alpha)^{1/2}/u$$

Duration of the interaction is given by:

$\omega t = \pi/2$, which leads to:

$$T_{max} = (\pi/2)*(\rho\ bd/2\sigma \tan \alpha)^{1/2}$$

Some important conclusions can be drawn from this model.

The maximum force ($F_{max}$) is:

- Proportional to the ice thickness and $(A_{surface})^{1/2}$
- Proportional to the impact velocity $V_o$
- Weakly dependent on the strength of ice and blade geometry
- Weakly dependent on the eccentricity (e)

The duration of impact is:

- Proportional to $A_{surface}^{1/2}$
- Inversely proportionally to $(\sigma_{cr})^{1/2}$ and $(\tan\alpha)^{1/2}$
- Not dependant on ice thickness

For the M V Robert LeMeur:

$\rho_i = 3/2 * 900$ kg

$u = 1 + 12 * 0.25^2/(1 + .5^2) = 1.6$
$b \sim 1$ m
$d \sim 0.5$ m
$h \sim 0.5$ m
$\sigma_{cr} \sim 4$ MPa
$\alpha \sim 7^o$
$V_o \sim 25$ m/s
$F_{max} = 0.25$ MN = 25 tonnes
$T_{max} \approx 0.03$ sec
$\omega \approx 48$ [1/s]
$X_{Gmax} = 0.32$ m
$X_{Amax} = 0.24$ m
$\alpha_{max} = 0.7$ RAD
$V_{Gmax} = 15.6$ m/s

Although these values seem reasonable, it is doubtful that a small (0.25 $m^3$) ice piece can withstand, intact, the force of 25 tonnes applied during 0.03 sec.

Also it should be noted that the total force acting on the blade should contain water drag on the ice piece at velocity of 15.6 m/s.

The drag is:

$$R = 1000 * 15.6^2 * 0.5^2 = 6.08 \text{ tonnes}$$

Interaction numeral is:

$$m V^2/(2 \nabla) = 0.4$$

This suggests that the piece would shatter before reaching equilibrium position.

### 7.5.3 Brittle Impact

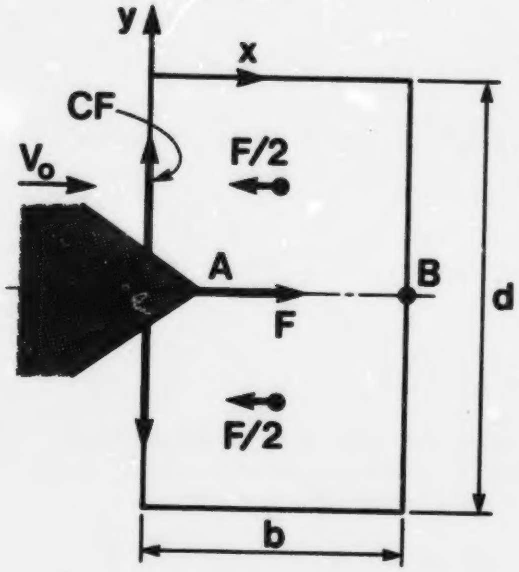
When an ice block is suddenly accelerated by the blade, large inertial forces are developed within the block. If these forces are not in a balance with the full width support, large bending moments and shear forces will develop (see Figure 7.5.3). These forces will create the stress field which, when the resulting tension is developed, will support crack propagation throughout the block. An exact model of the stress field requires FEM computations, therefore, we will adopt a simplified approach.

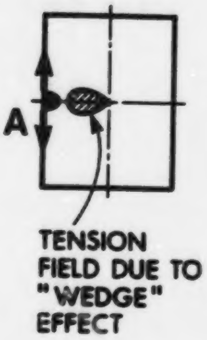
Tensile stress at the notch (Point A), (see Figure 7.5.3 for symbols):

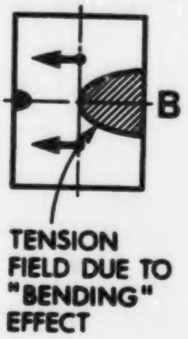
$$(\sigma_{tens})_A = cF/bh + cF * (b/2) * 6/hb^2 - F/2 * (d/4) * 6/hb^2$$

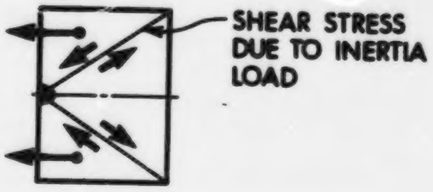
$$= F/bh * (4c - 3/4\ d/b)$$

Where c denotes a fraction of load (F), acting in a direction y-y.


y
x
CF
F/2
V₀
A
B
F
d
F/2
b


A
TENSION FIELD DUE TO "WEDGE" EFFECT

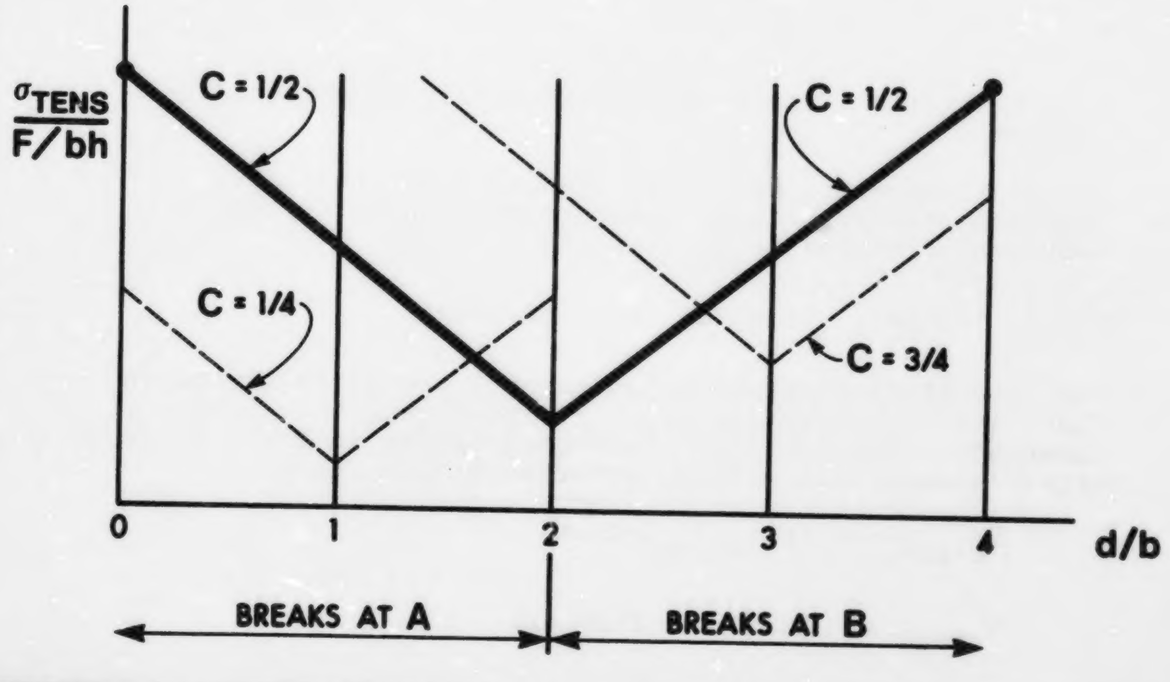

B
TENSION FIELD DUE TO "BENDING" EFFECT


SHEAR STRESS DUE TO INERTIA LOAD

FOR A WEDGE SECTION

$$\frac{F_y}{F_x} \cong C \cong \frac{\bar{b}}{\ell}$$

WHERE b IS THE WIDTH OF THE WEDGE AND $\ell$ IS ITS SUBMERGED LENGTH



| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: CRACK INITIATION<br>FIGURE No. 7·5·3 |
|---|---|---|

Tensile stress at the Point B:

$$(\sigma_{tens})_B = cF/bh + cF * (b/2) * 6/hb^2 + F/2 * (d/4) * 6/hb^2$$

$$= F/bh\ (-2c + 3/4\ d/b)$$

(Note that the stress concentration factors are not being used).

Depending on which stress is the larger one, the crack will initiate either at point A or B.

The ratio of d/b and the bluntness of the wedge determine whether the crack starts at A or B. In general, large d/b and a blunt wedge (small c) favors point B.

Having started the crack at either A or B, extending it takes very little energy. The crack extension force ($F_{crack\ ext}$) is calculated from:

$$F_{crack\ ext} \approx (K_{ic})^2/E$$

Using for $K_{ic} \sim 100\ kN/m/^{3/2}$ and $E = 4*10^9 Pa$ we will obtain:

$$F_{crack\ ext} \approx 2.5\ N$$

Thus extending a crack takes practically no effort (in vaccuum).

In water, however, the crack opening force must also overcome the hydrostatic pressure which creates the compressive stress ($\sigma_{hydro}$):

$\sigma_{hydro} = \gamma H$ (in the order of 10KPa)

The time of crack propagation through the block may be an important consideration for high speed impacts. Little is known about the speed of crack propagation in ice. It is often assumed, for various other materials, that:

$V_{crack} \sim 0.38\ V_{sound}$, where

$V_{sound} \approx (E/\rho)^{1/2} \sim 2100$ m/s

Which gives ($V_{crack\ ice}$) ≈ 800 m/s

For an ice block with a length of 1 m, the duration of the crack propagation is 1/800 sec. When the leading edge is travelling at a speed of approximately 30 m/s, the blade will immerse in the ice for a depth of 3.75 cm before the crack goes through. This additional immersion causes a significant force to be developed in addition to the crack initiation force. Of course the crack may deviate to one of the near-by edges of the ice block rather than going through the middle of the block. However, it is believed that "curved" cracks are slower than "straight" ones and therefore, the duration of crack travel may not change appreciably.

After the crack has run through the block, the two pieces will separate. The load on the blade tip will depend upon how fast the pieces are being pushed apart (see Figure 7.5.4).

We thus have identified 3 phases of the brittle impact:

- Development of the tension field
- Crack propagation
- Separation of the pieces

In the first phase, the limit force is dictated by the ability of the ice to sustain tension prior to crack propagation.

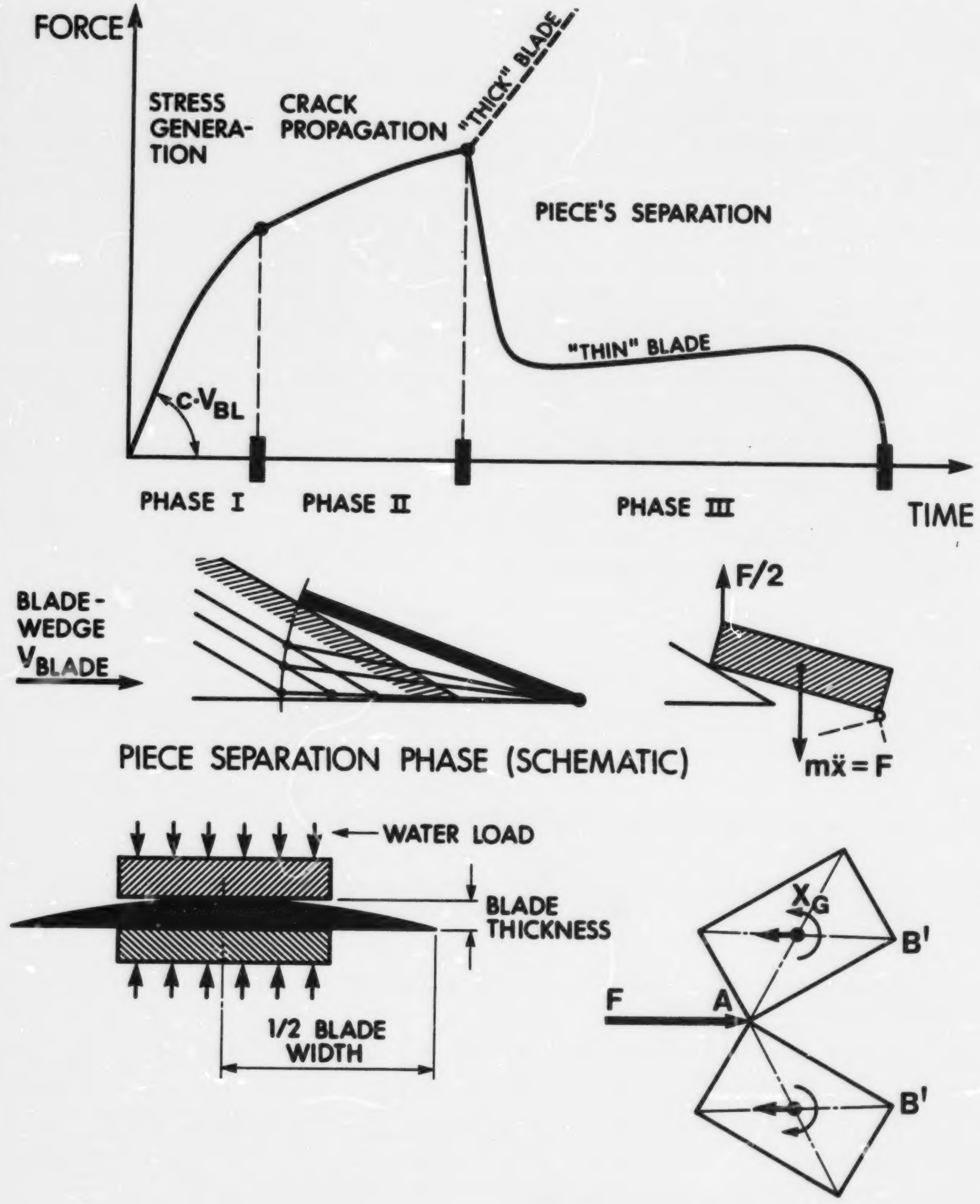
In the second phase, the limit force is dictated by the duration of crack propagation.

In the third phase, the limit force is dictated by the inertia of the ice blocks and blade edge geometry (i.e. by the speed of separation).

To estimate the load and the duration of each phase, we proceed as follows.

On the assumption that the crack is being initiated at Point A, and using

$c = 1,\ d/b = 1,\ h = b = d = 0.5\ \text{m},\ \sigma_{tens} = 1.5\ \text{MPa},$


FORCE
STRESS GENERATION
CRACK PROPAGATION
"THICK" BLADE
PIECE'S SEPARATION
"THIN" BLADE
C·V_BL
PHASE I
PHASE II
PHASE III
TIME
BLADE-WEDGE
V_BLADE
F/2
mẍ = F
PIECE SEPARATION PHASE (SCHEMATIC)
WATER LOAD
BLADE THICKNESS
1/2 BLADE WIDTH
X_G
B'
F
A
B'

**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** BRITTLE IMPACT

**FIGURE No.** 7·5·4

we obtain:

$$F_I = 11.5 \text{ tonnes}$$

Further, assuming $\sigma_{crack} = 20*10^6$Pa, the above load corresponds to the projected penetration area of:

$$\nabla/h = F/\sigma_{cr} = 0.11510^6/20*10^6 = 0.0057 \text{ m}^2,$$

but, from wedge geometry we have:

$$\nabla/h = x^2 * \tan\alpha, \ (\tan\alpha = ½)$$

So we obtain initial wedge penetration:

$$x = 0.1 \text{ m.}$$

In reality the load will be smaller by a factor of 10 due to stress concentration factors. Then the penetration will be less by a factor of $10^{1/2} = 3.2$.

Therefore realistically we can expect loads in the order of 1 to 10 tonnes and a penetration of about 3 cm.
In the second phase, the load will grow as long as the crack is propagating. Penetration (x) during this phase will be:

$$x = 0.5 \text{ m}/800 \text{ m/s} * 30 \text{ m/s} = 1.9 \text{ cm}$$

The force will be found by the direct proportioning of the phase I force:

$$F_{II} = 1.15 * (0.03 + 0.019)/0.03 = 1.9 \text{ tonnes}$$

Thus the force grows about 60% during the crack propagation stage.

Duration of this phase is

$$t_{II} = 0.5/800 = 0.0006 \text{ sec}$$

For the third phase we will proceed as follows:

As the blade passes between the broken pieces, it generates an out-of-plane force. The time which it takes to reach the centre of gravity of the broken piece is:

$t = (b/2 + \text{Blade Width}/2)/V_{blade}$

(In the example t = (0.25 + 0.5)/25 = 0.03 sec.)

In that time, the ice was accelerated through a distance equal to the blade thickness.

Assuming constant acceleration, we calculate the axial distance of the accelerating ice piece:

$$s_{blade} = at^2/2$$

For the MV Robert LeMeur blade we have:

$$a = 2s/t^2 = 2 * 0.052/0.032^2 = 115 \text{ m/s}^2$$

Force is then:

$F = m*a = 0.5 * 0.5 * 0.5 * 3/2 * 900 * 115 \text{ m/s}^2 = 1.9$ tonnes

To this value, the water drag and the hydrostatic pressure should be added.

The direction and point of application of this force depends on the blade's thickness distribution.

The separation of the pieces can also be initiated at Point B (see Figure 7.5.4). If it is then on the assumption of constant velocity of the blade during the interactions, we will obtain:

$$X_A = X_G\ (1 + 12\ e^2/(b^2 + d^2))$$

$$\ddot{X}_A = \ddot{X}_G\ (1 + 12\ e^2/(b^2 + d^2))$$

Splitting force before impact:

$$F_{B.Spl.} = m * \ddot{X}_G$$

After the impact:

$$F_{A.Spl.} = 2 * m/2 * \ddot{X}_G = m\ \ddot{X}_A/(1 + 12\ e^2/(b^2 + d^2))$$

Force After/Force Before = $1/(1 + 12\, e^2/(b^2 + d^2))$

For $b/d = 1/2$:

$$F_{\text{Aft Split}}/F_{\text{Before Split}} = 0.58$$

For $b \Rightarrow 0$:

$$F_{\text{Aft}}/F_{\text{Bef}} = 4/7$$

The major conclusions of this model are:

- The faster the impact, the higher the loads are for all 3 phases.
- The loads depend highly on the leading edge geometry.
- The loads depend on the ice stress field around the impact zone.
- The impact force direction may change rapidly depending on which direction the crack is propagating.
- The water induced force is an important component of the impact force in the third phase.

### 7.5.4 Milling Model

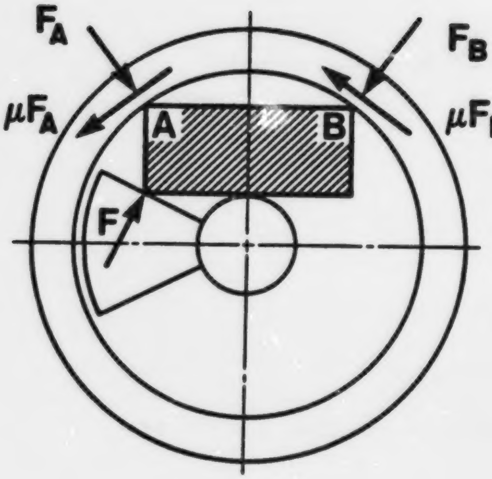
Milling is defined as a phenomenon where:

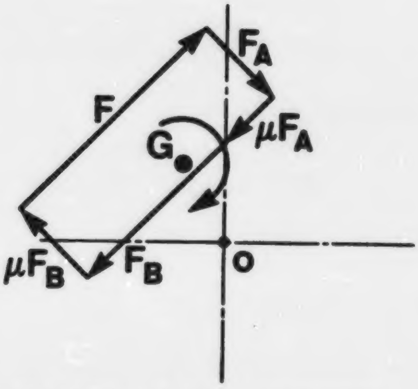
- Ice is hit repeatedly by number of blades.
- Ice piece geometric characteristics remain essentially similar throughout the process, except at the end of the milling, when the ice piece becomes small.

The geometry of milling is shown on Figure 7.5.5. The milling process is expected to develop as follows:

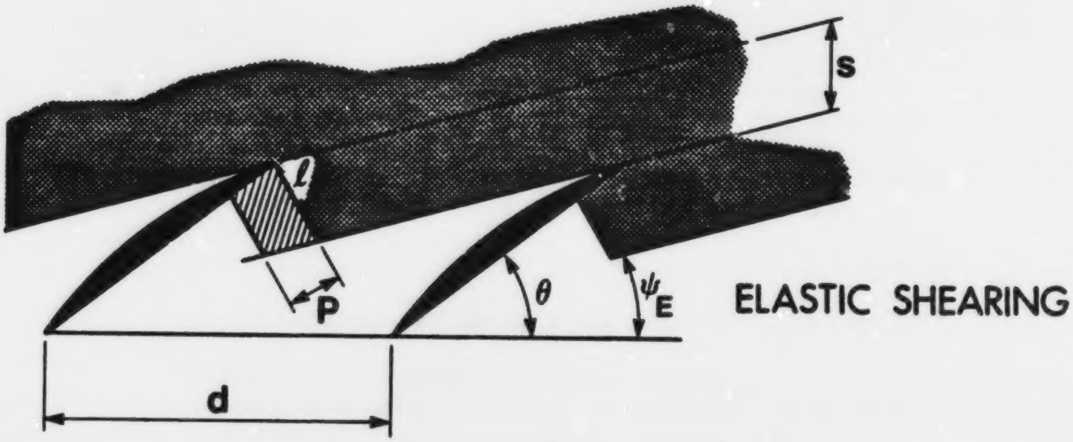
- Ice enters the nozzle ring at a velocity somewhat less than the water velocity due to the fact that it first bounces off the structure.

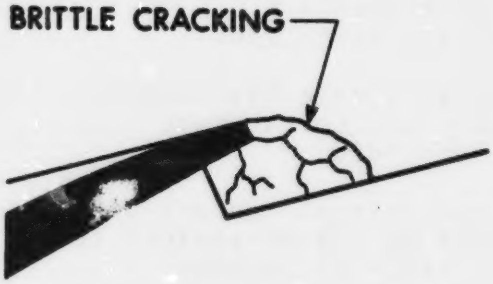
- For a large block, after the initial contact with the blade is made, the block is thrown against the inner walls of the nozzle, where it remains. Three local contact zones are needed to hold the ice against the ring. Pressure at these points will be high, therefore, friction will be high. Consequently, the rotation of the ice block will initially be slowed down.

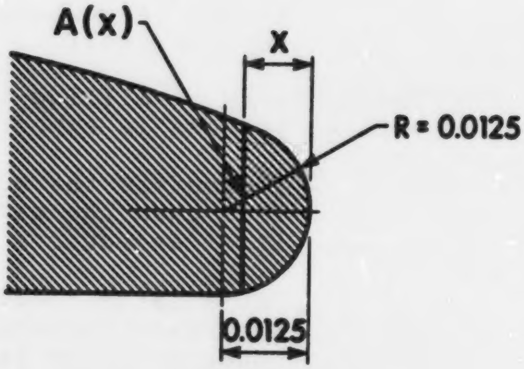

$F_A$
$F_B$
$\mu F_A$
$\mu F_B$
A
B
F


F
$F_A$
$\mu F_A$
G
$\mu F_B$
$F_B$
o

POLYGON OF FORCES


s
ℓ
P
θ
$\psi_E$
ELASTIC SHEARING
d


BRITTLE CRACKING


A(x)
X
R = 0.0125
0.0125

LEADING EDGE DETAIL

**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:**
**MILLING MODEL GEOMETRY**

**FIGURE No.** 7·5·5

- With inertia and friction resisting the rotation of the ice block, the ice will be effectively stationary relative to the rotating blades. Water pressure will "feed" ice into the blades, which will then "shave" the block.
- As the size of the ice block gets smaller, its resistance to the blade impacts diminishes. It will accelerate until it is sufficiently small to go through the propeller disk.

The amount of ice "fed" into the propeller is:

$$S = V_{ice}/(Z*n)$$

$V_{ice} \ll V_{water}$ for $V = 4$ m/s, $s = 0.30$ m.

As the blade immerses into the ice, the contact area will develop until the resultant force is large enough to shear a small piece off. It is likely that the shearing will be a brittle one, i.e. the shear crack will propagate through a distance $\ell$. Shear distance $\ell$ is defined as:

$$\ell \cong d \sin \varphi_e/\cos(\theta - \varphi_e) \cong s \cos \theta$$

The condition for shear is:

$$\sigma_{crush} * p = \sigma_{shear} * \ell, \text{ (p, } \ell \text{ as defined in 7.5.5)}$$

From which:

$$p = \sigma_s/\sigma_c * \ell$$

The force developed on the face of the blade is, taking $\sigma_s = 1$ MPa,

$$F_{crack} = \sigma_s * \cos \theta * V_{ice} * h_{ice}/(Zn)$$

For the MV Robert LeMeur:

$F_{crack} = 1 * 10^6 * \cos 23.6° * 4.05\text{m}/(4*3.5) = 13.5$ tonnes

This force is perpendicular to the plane of the blade at the point of contact.

If $\sigma_s$ is higher for the dynamic impact, the force will be proportionally higher.

This formulation, based on the static and elastic modelling of interaction, suggests that the force is:

- Proportional to ice strength
- Proportional to the cosine of the pitch angle
- Proportional to the axial velocity of ice
- Inversely proportional to the number of blades
- Inversely proportional to the RPS

In addition to the out-of-plane force, an in-plane force will develop due to the finite thickness of the leading edge.

This force will be spatially and temporally fluctuating as brittle cracking will take place. The cracking will be affected by the close proximity of the free edge, thus shattering of the milled layer of ice is expected.

The crack length, if propagated along a circular arc, has a length:

$$\ell_{crack} \cong 2\pi s/4 \cong 1.6\ s$$

Duration of the crack propagation is then:

$$t_{crack} = \ell_{crack}/V_{crack} \cong 1.6\ s/(0.38\ V_{sound}) \cong 4.1\ V_{ice}/(Z*n\ V_{sound})$$

The depth of blade immersion during that time is:

$$X = V_{blade} * t_{crack} = 4.1\ V_{blade} * V_{ice}/(Z*n\ V_{sound}) \quad \text{or,}$$

$$X = 25.8\ R*\ V_{ice}/(Z\ V_{sound})$$

and the force developed at the leading edge is:

$$F = p_{crush} * A(x)$$

For the MV Robert LeMeur:

$$X = 4.1 * 25\ m/s * 4\ m/s/(4 * 209/60 * 2100) = 0.014\ m$$

Thus the immersion depth will be small before the crack propagates through the ice.

The out-of-plane force is then:

$F = \sigma_{crush} * x * h$ ice, which, for the MV Robert LeMeur translates into:

$$F = 20 * 10^6 * 0.014 * 0.5 = 14 \text{ tonnes.}$$

Taking the leading edge cross-section of radius 0.0125 m, the projected area A(x) is approximately equal to the thickness of the blade.

$$F = p_{crush} * h_{ice} * t_{blade}$$

Taking $p_{crush} \approx 3 * \sigma_{crush} \approx 6$ MPa, $h_{ice} = 0.5$ m, $t_{blade} = 0.025$ m, we will obtain:

$F_{6MPa} = 7.5$ tonnes, for p = 20 MPa,

$F_{20MPa} = 25$ tonnes

Note that the thickness of ice in the above formula is dependent on the orientation of the blade against the ice block, the maximum thickness being $\sqrt{2}$ times the ice thickness.

The force is:

- Proportional to the strength of ice and its thickness
- Proportional to the thickness of the blade
- Highly dependent on the leading edge geometry

The block chopped-off the parent ice block has a volume of approximately:

$\nabla \cong h_{ice} * s^2$, which translates into 0.042 $m^3$, or 40 kg.

This mass is accelerated downstream with the velocity ($V_{p.s.}$) previously mentioned. Since the density of ice is not too different from that of water, the force needed to accelerate the ice piece will be of similar magnitude to that of hydrodynamic origin.

Depending on the thickness distribution of the blade, the blade may pull in or repell the ice block during milling process as shown in Figure 7.5.6.

The total duration of the milling event is dependent upon the size of the block being milled:

$$T_{mill} = c^* (\ell_{ice}/V_{ice})$$

Where c is a constant reflecting deceleration of ice piece, its rotation and other non-steady phenomena.

For $V_{ice} \cong 4$ m/s, $\ell_{ice} \cong 1$m,
$T_{mill} = c * 0.25$ sec

For an individual blade passing, duration of milling is:

$$T_{mill\ blade} \cong 2\ \pi\ R/4\ V_{blade} = 0.25/RPS$$

For the MV Robert LeMeur:

$T_{mill\ blade} \cong 0.072$ sec. (90° of rotation of the blade)

Within this time span the ice force will exhibit several peaks, each of a few milliseconds duration, corresponding to the chipping-off of the edge of ice block.

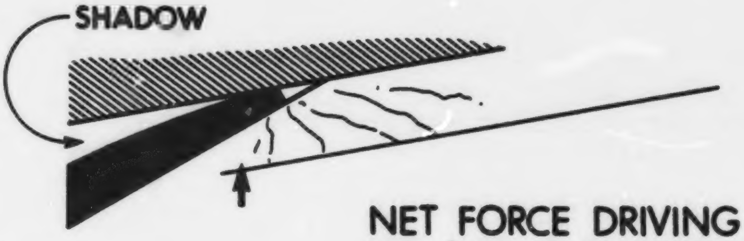
The number of blade impacts during a milling event is:

$$N = \ell_{ice}/s = \ell_{ice}\ Z*n/V_{ice} \approx T_{mill} * Z*n$$

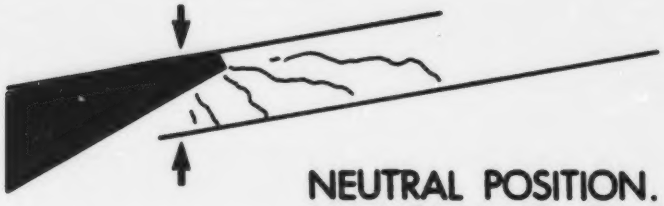
In summary, the following observations can be made.

- Out-of-Plane Forces: They are proportional to the strength of ice, cosine of pitch angle, velocity of ice inflow and inversely proportional to the number of blades and RPS. Force is also proportional to the ice thickness. A major unknown parameter is the dynamic shear strength of ice.

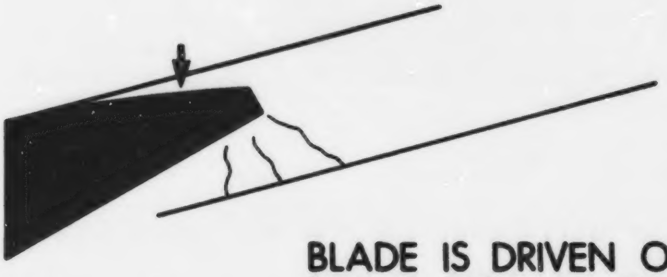
- In-Plane Forces: They are proportional to the thickness of ice, thickness of blade, and dynamic crushing pressure. They are very dependent on the brittle behaviour of ice and the details of the blade edge geometry.



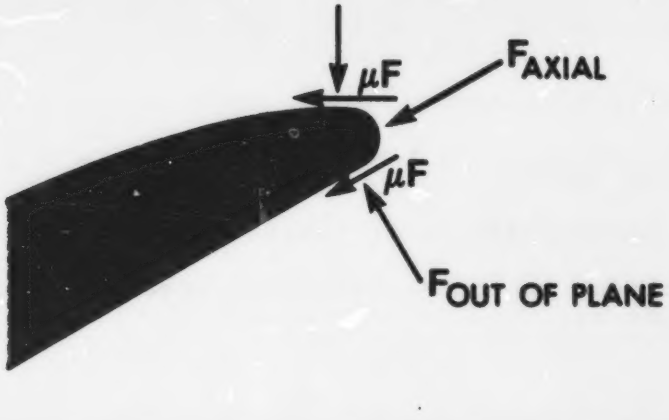
NET FORCE DRIVING BLADE INTO ICE (ICE IS SUCKED IN)



NEUTRAL POSITION. BLADE IS MAINTAINING ITS DEPTH OF MILLING



BLADE IS DRIVEN OUT OF ICE (ICE IS REPELLED BY THE BLADE)


$\mu F$
$F_{AXIAL}$
$\mu F$
$F_{OUT\ OF\ PLANE}$

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DRILLING
LIMITED

MEASUREMENT OF ICE
PROPELLER INTERACTION
PARAMETERS

TITLE:
MILLING MODEL

FIGURE No. 7·5·6

- Impulse Durations: Blade impulses last approximately 90° of rotation. The whole milling time is proportional to the length of the ice piece and is inversely proportional to the speed of the ice inflow.

### 7.5.5 Single Impact Model

In this type of collision, the ice block is sufficiently small so that it interacts with only a few blades before being shattered or pushed through. Interaction is of the "global" type. Therefore, the magnitude of the force of interaction depends upon the load bearing capability of ice block, before it splits or shatters.

As identified earlier, during the first phase of interaction, the stress field has to be developed, producing crack initiation force:

$$F_I = \sigma_{tens} * b * h\ (4c - 3/4\ d/b) * k$$

where b, h, d are width, thickness and length of the ice block, and k is the stress intensity factor, set at 1 for the time being. Factor c depends on the geometry of the blade edge which defines how much of the total force is directed sideways, i.e.:

$$F_{sideways} = c\ F_{forward}$$

Taking c as 1, we will have, for the MV Robert LeMeur:

$F_I \leq 11.5$ tonnes, and corresponding penetration of approximately 3 cm.

Penetration in the second phase will depend on the speed of crack propagation, $V_{crack}$, set at 800 m/s.

Penetration distance is then:

$$x = \ell_{ice} * V_{blade}/V_{crack} = 0.5 * 25\ m/s/800\ m/s = 1.6\ cm$$

Thus the total penetration is of the order of 4.6 cm.

At that penetration, the cross sectional area of the blade can be calculated as:

$A_{\otimes} = t_{BL} * (x/d/2)^{0.276} * h_{ice}$ (see Figure 7.5.7)

which gives, for $r/R = 0.7$:

$$A_{\otimes} = 0.0687 * (4.6/60.4)^{0.276} * h_{ice} = 0.034 * h_{ice}$$

For 0.5 m thick ice, $A_{\otimes}$ becomes 0.017 $m^2$ (above is valid for the central impact).

Force at the end of the second phase is therefore:

$$F_{II} = 0.017\ m^2 * p,$$

which, when taking p at 20 MPa produces 34 tonnes in a predominantly in-plane direction.

For the non-central impact which produces large rotating moment on the ice block, the impact force will be out-of-plane. This will result in shearing of the pieces essentially similar to that occurring in the milling process. In that scenario, loads are less than those computed above, however, their direction is out-of-plane.

In summary, the loads developed during the single impact are:

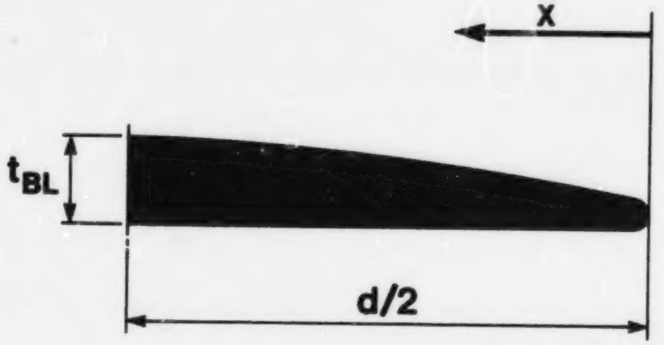
- Proportional to the width and thickness of the ice block
- Proportional to the strength of ice
- Proportional to the speed of the blade
- Inversely proportional to the speed of crack propagation

where proportionally implies linear or nonlinear dependency.

## 7.6 Discussion of Results

- Shrouded propeller ice-blade interaction has been found to be a global process, governed by the strength and geometry of the ice block.

- Two main types of interaction have been studied, milling and single impact. In milling, the shear strength of the ice and the proximity of the free



FOR $r/R = 0.7$

$$\frac{t(x)}{t_{BL}} = \left(\frac{x}{d/2}\right)^{0.276}$$ EVERYWHERE EXCEPT NEAR THE EDGE

TITLE: GEOMETRY OF BLADE SECTION

FIGURE No. 7·5·7

edge governs the maximum force level. In the single impact, the crack propagation through the whole block governs the magnitude of the maximum force.

- Elastic, plastic, and brittle models of ice behaviour have been explored. All of the models use ice properties which have unknown values (high speed crushing strength, shear strength and elastic modulus, velocity of crack propagation). All of the models show that the force is proportional to:

  The thickness times the linear dimension of ice;
  The thickness and velocity of the blade, and;
  The "strength" of ice.

- The maximum force is very dependent upon the details of the leading edge geometry. Forces of 20 to 30 tonnes per blade can be generated in the MV Robert LeMeur, of predominately in-plane direction. The magnitude of the forces depends on the high speed dynamic pressure between the blade and the ice. The value of this is, at the present time, unknown.

- Water can create very significant loads in addition to the loads of impact (blocking, shadowing and drag). The lower the pitch angle, the lower the loads (all considered). Duration of interaction with single blade can be of 90° (80 milliseconds) for milling and few milliseconds for single impact. A summary of the models is provided below.

SUMMARY OF ICE LOADS

| MODEL | POINT OF APPLICATION | MAGNITUDE | DIRECTION | COMMENTS |
|---|---|---|---|---|
| Milling impact | Leading edge | +25 | In-plane | Highly dependent on dynamic strength of ice |
|  | Pressure side | +15 | Out of plane |  |
| Single impact | Leading edge | +34 | In-plane depending on ice block orientation | As above, sensitive to orientation of ice block |

## 7.7 List Of Ice Properties Used In All Modelling Of Ice Propeller Interaction

| | |
|---|---|
| Elastic Modulus | $E = 4 \times 10^9$ Pa |
| Crushing Pressure | $\sigma_{cr} = 5 - 25$ MPa |
| Velocity of Sound | $C_o = 2100$ m/s |
| Density | $\rho = 910$ kg/m$^3$ |
| Shear Stress | $\tau = \sigma_s = 1.0$ MPa |
| Critical stress Intensity Factor | $K_{IC} = 100$kN/m$^{3/2}$ |

# 8. BLADE MODEL

## 8.1 Introduction

The purpose of this section is to develop an understanding of the relationship between ice loads and stresses anywhere in the blade.

The simple model we shall use for quantitative assessment of the stresses is the cantilever beam with varying stiffness. The twist of the blade is assumed not to have an influence on the stress distribution within the blade.

## 8.2 Blade Properties

Listed below are the structural properties of the blade. (After LIPS Specification):

| r/R | LENGTH m | AREA $m^2$ | SECTION THICKNESS m | INERTIA $m^4$ $10^{-6}$ | MODULUS $m^3$ $10^{-6}$ |
|---|---|---|---|---|---|
| 1.0 | - | - | - | - | 0 |
| 0.9 | - | - | - | - | 170.0 |
| 0.8 | 1.348 | 0.0421 | 0.0521 | 9.37 | 359.6 |
| 0.7 | 1.208 | 0.514 | 0.0687 | 19.25 | 560.4 |
| 0.6 | 1.046 | 0.581 | 0.0868 | 33.62 | 714.6 |
| 0.5 | 0.886 | 0.0607 | 0.1083 | 55.31 | 1021.4 |
| 0.4 | 0.722 | 0.0680 | 0.1386 | 94.47 | 1363.2 |
| 0.367 | 0.666 | 0.0708 | 0.1520 | 114.90 | 1512.4 |

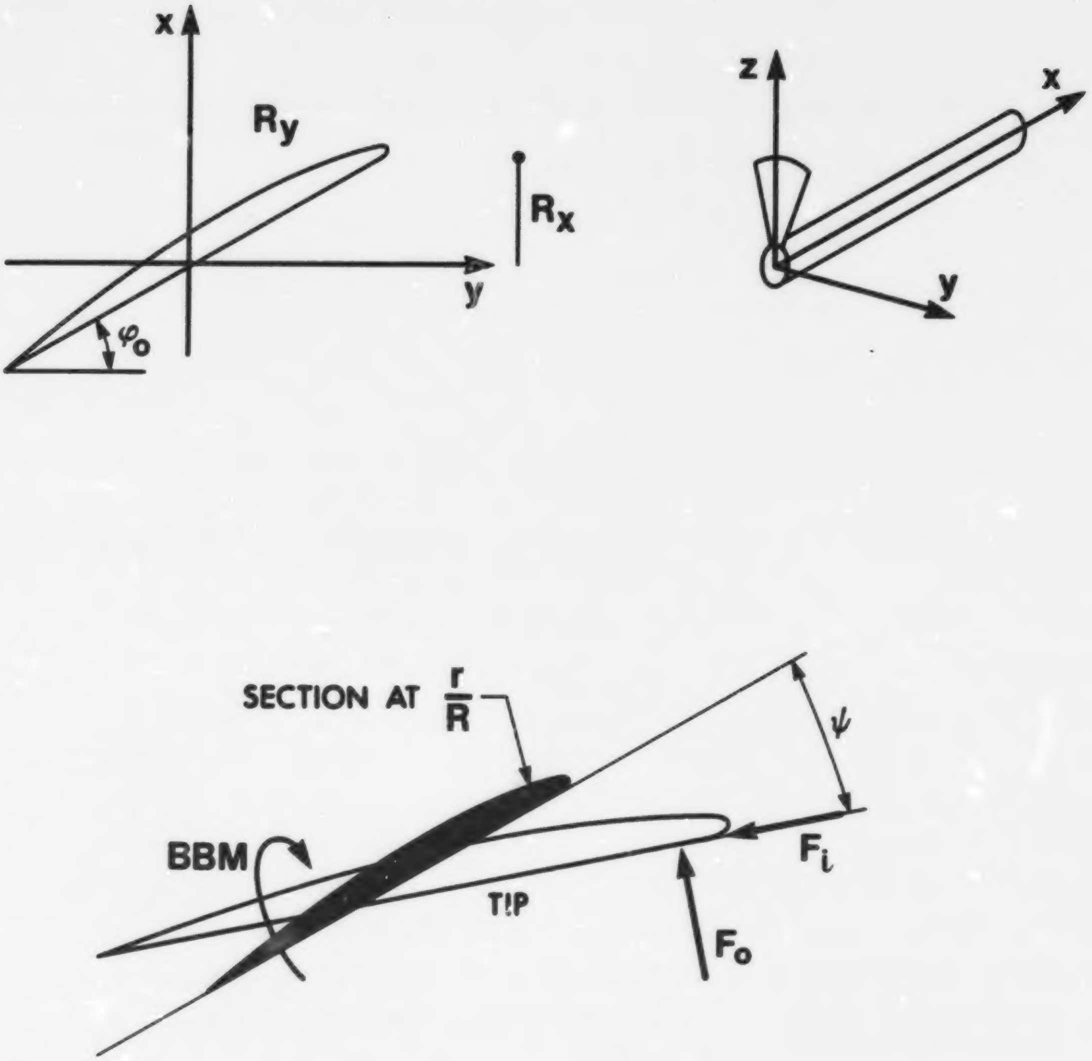
The material of the blade is CUNIAL BRONZE, having an elastic modulus $E = 1.3*10^{11}$ Pa (60% of steel) and a specific gravity $\gamma$ = 7.6 tonnes/$m^3$. Poisson constant $\upsilon$ is assumed to be 0.3.

## 8.3 Force Definitions

Take a fixed coordinate system xyz having its origin at the centre of the hub (see Figure 8.3.1). If the force is given by:

$$F_x = F\cos x$$
$$F_y = F\cos y$$
$$F_z = F\cos z$$

(where cosx, cosy, cosz are cosine directional of the force vector), and the point of load application is given


x
R_y
R_x
y
φ_o
z
x
y
SECTION AT r/R
ψ
BBM
F_i
TIP
F_o

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PARAMETERS

TITLE: FORCE DEFINITIONS

FIGURE No. 8·3·1

by $(R_x, R_y, R_z)$ then we will have:

**Blade Bending Moment**

$$BBM=(F_x \cos\varphi_o - F_y \sin\varphi_o)*(R_z - r_o)+F_Z *(R_y \sin\varphi_o - R_x \cos\varphi_o)$$

**Blade Spindle Torque**

$$BST = F_y R_x - F_x R_y$$

**Blade Shear Force**

$$BSF = +F_x \cos\varphi_o - F_y \sin\varphi_o$$

**Blade Axial Force**

$$BAF = F_x \sin\varphi_o + F_y \cos\varphi_o$$

**Blade Radial Force**

$$BRF = F_z$$

### 8.4 Stress Due to Simple Bending

The blade of the MV Robert LeMeur has a twist of 17.9° along its length. This introduces torsional effects in the stress field of the blade which can be resolved with an aid of FEM (Finite Element Method). In this treatment those effects are neglected however and the bending in the principal axis of the blade is considered only. We have:

$$BM\,(r/R) = R\,(R_o/R - r/R) * (F_i * \sin\psi + F_o \cos\psi).$$

$\psi$ being the angular twist between the blade section at radius $R_o$ and that at radius $r$.

For $R_o/R = 1$, we have:

| r/R | $\psi$ | $\sin\psi$ | $\cos\psi$ |
|---|---|---|---|
| 1.0 | 0 | 0 | 1 |
| 0.9 | 1.6 | 0.028 | 0.999 |
| 0.8 | 3.6 | 0.063 | 0.998 |
| 0.7 | 5.7 | 0.099 | 0.995 |
| 0.6 | 8.5 | 0.178 | 0.989 |
| 0.5 | 11.4 | 0.198 | 0.980 |
| 0.4 | 16.9 | 0.291 | 0.957 |
| 0.375 | 17.9 | 0.307 | 0.951 |

From this table it is evident that the in-plane force should produce approximately 31% of the out-of-plane blade bending moment.

Assuming $F_i = 0$, for the $F_o$ applied at $r/R = 0.8$ the calculations of the stresses along the blade are performed using the formula:

$$BM/F_oR = (0.8 - r/R) * \cos\bar{\psi} \text{ where } \bar{\psi} = \psi - 3.6^{\circ}$$

| $r/R$ | BM | $SM(r/R)$<br>$10^{-6}$ | $\sigma_m = BM/(SM.F_oR) * F_oR$ |
|---|---|---|---|
| 1.0 | - | - | - |
| 0.9 | - | - | - |
| 0.8 | 0.0 | 360 | 0 |
| 0.7 | 0.1 | 560 | 0.00018 |
| 0.6 | 0.2 | 775 | 0.00026 |
| 0.5 | 0.3 | 1021 | 0.00029 |
| 0.4 | 0.39 | 1363 | 0.00029 |
| 0.375 | 0.41 | 1512 | 0.00027 |

Note that the $\sigma_m$ reaches the maximum at about $r/R = 0.5$ and then decreases.

For the positions of the force application other than $r/R \neq 0.8$, the same procedure can be employed.

The tip deflection of the straight cantilever beam under the point load is calculated as follows:

$\delta_{tip} = PL^3/(3EI)$, and the stiffness $k = P/\delta_A = 3EI/\ell^3$

Taking the "average beam" properties values:

$$k = 3 * 1.3*10^{11} * 31.8*10^{-6}/0.94^3 \cong 1.5*10^7 \text{ N/m}$$

Thus 1 tonne gives $\delta = 10^4/1.510^7 = 0.0007$ m

For a tapered beam, however, having:

$$I\ (r/R = 0.9) = 2.5*10^6,$$

$$k = 3 * 1.3*10^{11} * 2.5*10^{-6}/0.94^3 = 1.1710^6 \text{ N/m}$$

and

$\delta_{tip} = 0.0085 * 0.2 = 0.0017$ m

where 0.2 is the taper multiplier.

Thus 2 mm/1 tonne load is anticipated.

## 8.5 Added Mass Calculations

Take a freely vibrating beam-blade, as shown on Figure 8.5.1. We will treat the beam segments between nodes as independently vibrating beams. On the average, for the n-th mode of vibration we have n elements vibrating. Each element has a length of L/(n+ 1). Thus added mass for each node can be approximated by the sum of n added masses of n independently moving elements.

Using the formulation from the Reference 8.1, which assesses the added mass of rectangles $M_i$ in functions of their geometry, we obtain:

$$M_i = \rho\ (6.3\ a_i^2\ b_i^2/(a_i^2 + b_i^2)1/2 + 3.5\ a_i b_i (c)1/2$$

Putting $c = 0.025$ m, $b = 0.5$ m,
$a = 0.5$ m, $b_i = b/n = 1$,

We will get:

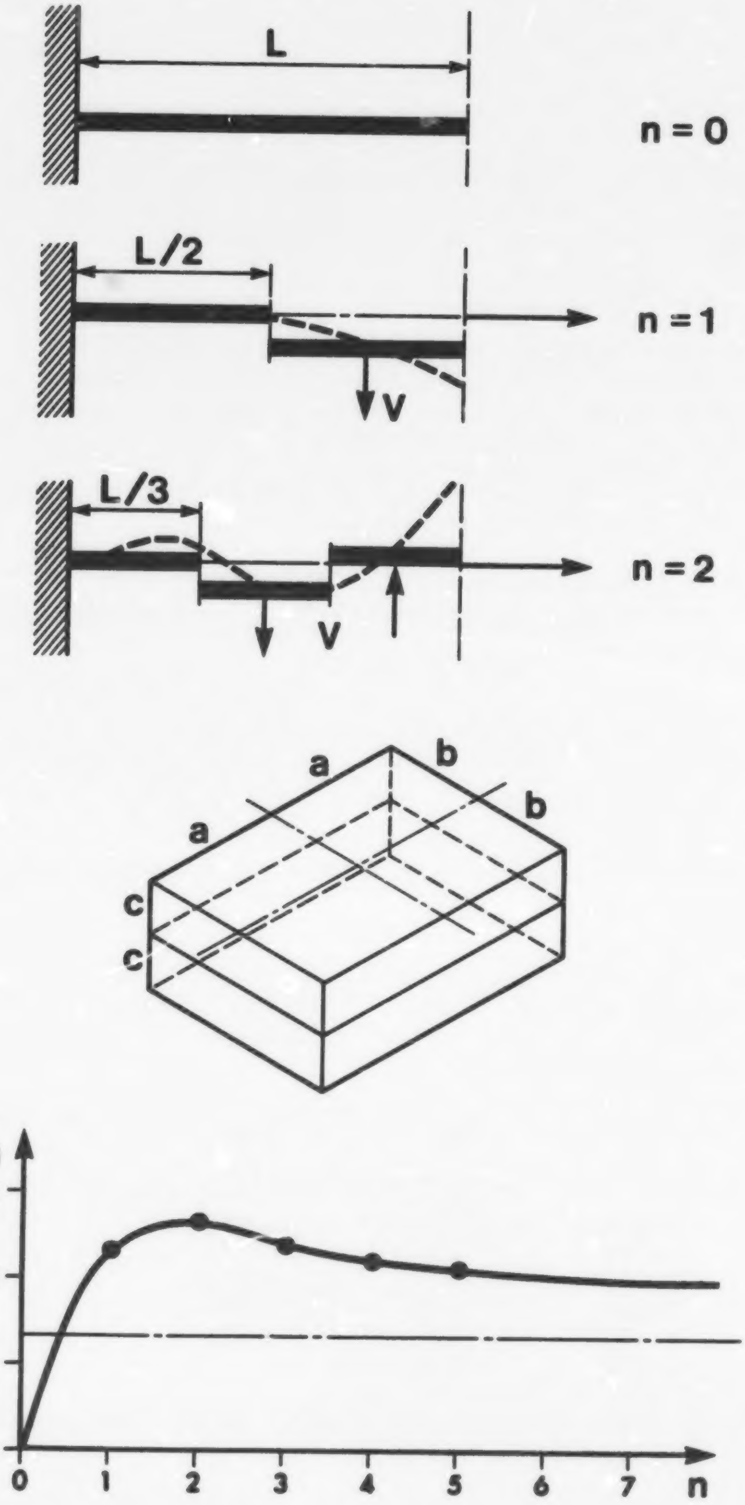
$$M\ (n) =$$
$$\rho(0.789\ n/(n+1))/((n+1)^2 + 1)^{1/2} + 0.138/(1 + 1/n) = \rho\lambda(n)$$

Calculations are shown below:

| n | λn | $M_{virt}$ | $M_{tot}$ | Freq Drop |
|---|---|---|---|---|
| 0 | 0 | 0 | 452 | 0 |
| 1 | 0.245 | 245 | 697 | 24% |
| 2 | 0.258 | 258 | 710 | 25% |
| 3 | 0.247 | 247 | 700 | 24% |
| 4 | 0.234 | 234 | 686 | |
| 5 | 0.223 | 223 | 675 | |
| ∞ | 0.138 | 138 | | |

If the blade was treated as a rigid body only, the added mass calculation would have been:

$$M_{tot} = 1000\ (6.3 * 1/8(2)^{1/2} + (3.5/4(0.05/2)^{1/2}) = 695 \text{ kg}$$


L
n = 0
L/2
n = 1
V
L/3
n = 2
V
a
b
a
b
c
c
λn
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7
n

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**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

TITLE:
SCHEMATIC FOR ADDED MASS CALCULATION

FIGURE No. 8·5·1

$M_{tot}$ = 2.54 times the mass of the blade and the reduction in frequency would have been 159%.

## 8.6 Frequency Calculations

An estimate of the average moment of inertia is done as follows:

| r/R | $I * 10^6$ | Multiplier |
|---|---|---|
| 1 | 0 | 2 |
| 0.0 | 2.5 | 2 |
| 0.8 | 9.37 | 2 |
| 0.7 | 19.25 | 2 |
| 0.6 | 33.62 | 2 |
| 0.5 | 55.31 | 2 |
| 0.4 | 94.47 | 1 |
| 0.376 | 114.90 | - |

which gives $I_{av} = 31.8*10^{-6} m^4$. In a similar way, the average cross-section area is estimated to be:

$$A_{av} = 0.05 \text{ m}^2$$

Using an "average" (non-tapered) beam method we arrive at

$$\omega_n = k^2 \, (EIg/A\gamma)^{1/2}$$

where, for the first mode (n = 1), $k\ell = 1.875$. Substituting, we will get

$$\omega_{n=1} = 0.411 \qquad f = 65 \text{ Hz}$$

For a tapered beam (Ref. 4), Case 1:

$$h_o = 0.15, \; h_{tip} = 0, \; b = b_o = 1 \text{ m}$$

where $\rho$ radius is equal to $(I/A)^{1/2} = 0.0993$ in, $\ell = 37$ in, fn = 124 Hz

Material correction for non-steel is:

$$F_{ni} = f_{ns} \, (E\gamma_s/Es\gamma)^{1/2} = \underline{99 \text{ Hz}}$$

Thus, using tapered beam model, we arrive at:

$f_{n1} = 99$ Hz for $n = 2$

$f_{n1}/f_{n2} = 0.349$

$f_{n2} = 283$ Hz

Both values are for in-air conditions.

### 8.7 Inertial Effects

Take a blade beam, loaded suddenly with impulse force F, as shown on Figure 8.7.1. Before the flexural wave will reach the foundation producing a reaction, the inertia of the beam will produce the reaction load, which will result in the bending moment at the foundation:

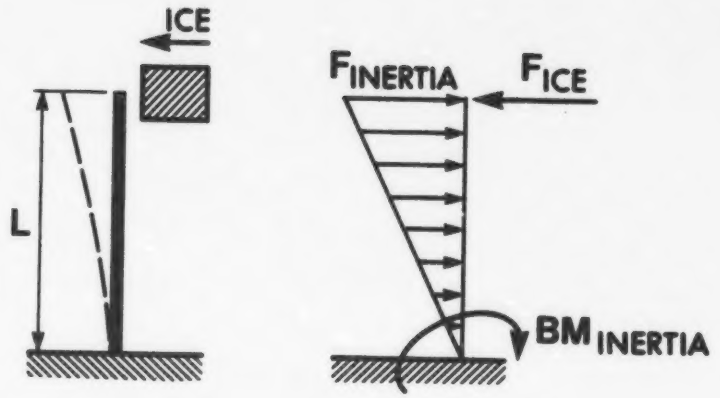
$$BM_{inertia} = F_{ice} * L - 2/3\ L * F = FL/3$$

Which is one third of the static load generated bending moment.

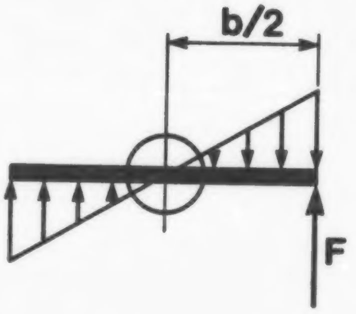
For a spindle torque inertia, similar reasoning leads to:

$$BM = -Fb/4$$

This effect will be investigated in detail in the post-testing phase, and documented in the final report.


ICE
L
F_INERTIA
F_ICE
BM INERTIA

BLADE
BENDING
INERTIAL
EFFECT



SPINDLE
TORQUE
INERTIAL
EFFECT

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**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** INERTIAL EFFECTS

**FIGURE No.** 8·7·1

## 9. YOKE PIN MODEL

### 9.1 Introduction

The purpose of the yoke pin model is to derive a mathematical expression relating the load applied at the propeller blade to the reaction of the yoke sliding block. The factors we shall take into account are the geometry of the blade and yoke pin plus frictional effects between the blade carrier and the hub body.

The load applied to the blade produces a spindle torque which is then transmitted through the blade body. Frictional forces between the blade carrier and hub body will produce a torque resisting the applied torque. The yoke pin will provide the remaining resisting torque. Thus we can write:

$$Qapp = Qpin + Qcentrifugal + Qbinding$$

eq: 9.1

Where:

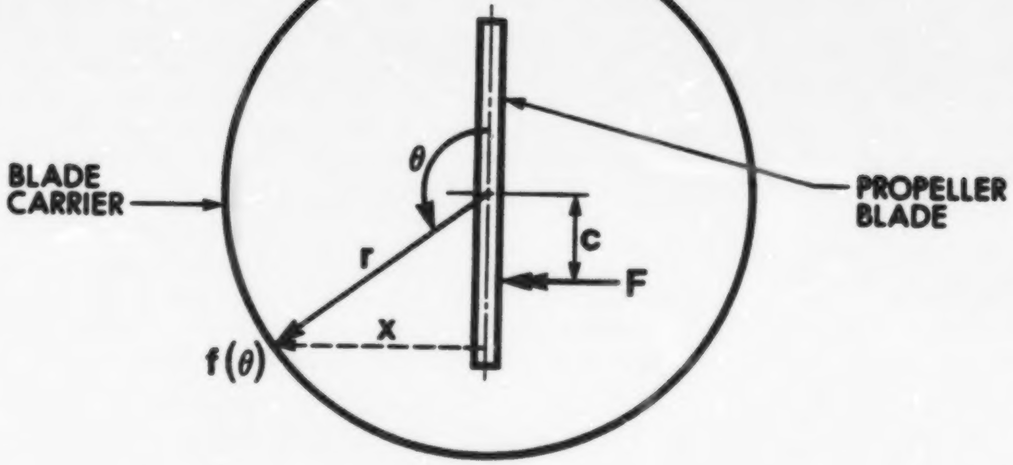
Qapp = applied torque.
Qpin = resisting torque of yoke.
Qcentrifugal = friction torque due to centrifugal force of blade, and;
Qbinding = friction torque due to applied load.

We now make the following definitions:

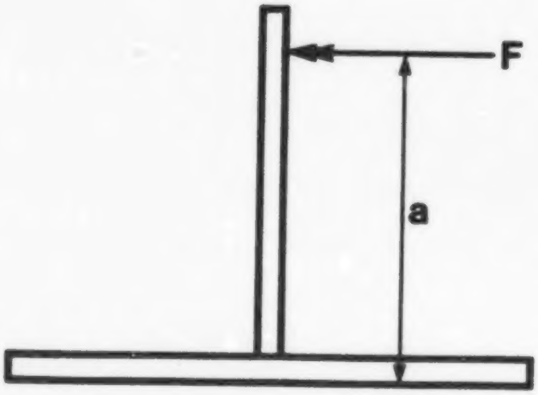
$r$ = radius of blade carrier bearing surface;
$c$ = radius lever arm of applied load from blade axis;
$rp$ = radius of yoke pin from blade center;
$a$ = height of applied load above blade carrier bearing surface;
$\mu$ = coefficient of friction between blade carrier and hub body;
$F$ = applied load, and;
$R$ = reaction of yoke pin.

See Figure 9.1.1 for illustrations of the loading situation.

Thus we can write the following:


BLADE CARRIER
PROPELLER BLADE
θ
r
c
F
x
f(θ)

TOP VIEW



SIDE VIEW

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MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE: GEOMETRY OF FORCES

FIGURE No. 9·1·1

$Q_{app} = F * c$ eq: 9.2

$Q_{pin} = R * r_p$ eq: 9.3

$Q_{centrifugal} = \mu * N * r$ eq: 9.4

## 9.2 Calculation of Friction Torque Due to Applied Load

To calculate this quantity we assume that the reactions of the hub to the applied load $F(\Theta)$ at the angle $\Theta$ is given by:

$$F(\Theta) \propto x$$

Thus: $F(\Theta) = k \sin\Theta$, where k is a constant,

From balance of moments:

$$\int_0^{90} F(\Theta) * x \, d(\Theta) = F * a/4$$ Thus:

$$\int_0^{90} k \sin\Theta * r \sin\Theta \, d\Theta = F * a/4$$

By solving the integral and solving for k we obtain:

$k = F * a/r$ Thus:

$F(\Theta) = F * a \sin\Theta/(r)$

The frictional torque Qbinding is thus given by:

$$Q_{bind} = 4\mu \int_0^{90} r * F(\Theta) \, d\Theta$$ Thus:

$Q_{binding} = 4\mu F * a$ eq: 9.5

Substituting equations 9.2 to 9.5 into equation 9.1 we obtain:

$F * c = R * r_p + \mu * N * r + 4\mu F a$ eq: 9.1

or:

$R = [F(c - 4\mu a) - \mu N r]/(r_p)$ eq: 9.7

Essentially what equation 9.6 or equation 9.7 is indicating is that for a given applied spindle torque, the yoke pin reaction will be greater if the load is applied near the root of the blade rather than near the tip of the blade.

### 9.3 Comparison of Model With Field Data

To obtain an estimate of the coefficient of friction we will use data obtained from the physical calibrations performed on the system. We shall use load points which have approximately the same value of "c" but different values of "a". The difference in yoke pin reaction is assumed to be due to the frictional effects. From equation 9.7 a graph of R versus F will have a slope:

$$S = [c - 4\mu a]/(rp)$$

Thus for two load points 1 or 2:

$$S_1/S_2 = c_1 - 4\mu a_1/(c_2 - 4\mu a_2)$$

but since $c_1 = c_2$

$$S_1/S_2 = c - 4\mu a_1/(c - 4\mu a_2)$$

Thus $\mu = c\ (S_1-S_2)/[4\ (a_2S_1-a_1-S_2)]$ eq: 9.8

Using data from Case 1, load Points 2 and 29 (see Section 3.2) we obtain an estimate of the coefficient of friction $\mu = 0.06$. Furthermore, the reaction of the yoke load pin when the blade was loaded near the tip was actually less than when the blade was loaded near the blade root. Further investigation will be presented in the remaining reports of this project.

# 10. TORSIONAL AND LONGITUDINAL SHAFT MODEL

## 10.1 Introduction

The purpose of developing a propulsion train model is to relate propeller shaft response to ice induced blade loads. The propeller blade measurement system is not very sensitive to forces in the plane of the blade. However, forces in this plane are quite strongly coupled to the shaft torsion. Hence, by using the measured shaft response in conjunction with the response model, estimates of force in the plane of the propeller blade may be made. By comparing this data with the measured blade forces, the estimates of the directions of the applied loads can be made.

Longitudinal and torsional models with three degrees of freedom and lumped mass were developed with the aid of the Hewlett Packard 9845B desk top computer (see Appendix H and I). Using these models, torque and thrust waveforms based on observed blade results are applied at the propeller. The resulting waveforms on the shaft, where torque and thrust strain gauges are located, were then calculated, plotted and compared with the measured shaft response.

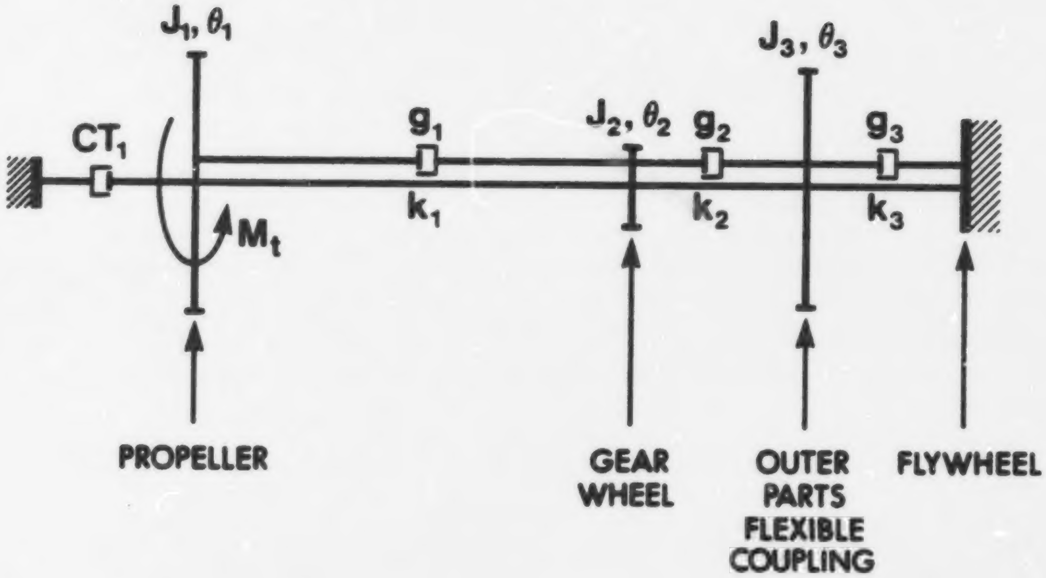
The damping for the first modal response was initially estimated by calculating the logarithmic decrement from measured data. The damping ratio for the propeller blade and the shafting was then varied until the damping measured on the shaft torque and thrust gauges matched the output of the model.

The longitudinal natural frequencies are approximately five times higher than the torsional natural frequencies. Therefore, mode coupling between the longitudinal and torsional shafting vibration can be neglected (Ref 10.3).

## 10.2 Torsional Model

The torsional model used is shown in Figure 10.2.1. The solution for the response of the model to an arbitrary input torque at the propeller is derived by using the modal superposition technique (Ref 10.1). The equation of motion of the propulsion model is:

$$[J][\ddot{\theta}] + [G_T][\dot{\theta}] + [C_T][\dot{\theta}] + [K_T][\theta] = [F_t]$$



$J_1, \theta_1$
$J_3, \theta_3$
$CT_1$
$g_1$
$J_2, \theta_2$
$g_2$
$g_3$
$k_1$
$k_2$
$k_3$
$M_t$
PROPELLER
GEAR WHEEL
OUTER PARTS FLEXIBLE COUPLING
FLYWHEEL

CANADIAN MARINE DRILLING LIMITED

MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE: ROBERT LEMEUR TORSIONAL MODEL

FIGURE No. 10·2·1

Where: $[J]$ = Mass moment of inertia matrix;
$[G_T]$ = Shaft damping matrix (proportional to $[K_T]$);
$[C_T]$ = Propeller damping matrix (only one non-zero element);
$[K_T]$ = Torsional stiffness matrix;
$[F_t]$ = Force matrix (torque on propeller blade), and;
$[\theta]$ = Twist of shaft at each node.

The twist of the shaft at each node is solved for each point in time. The torque on the shaft where the gauges are located is then calculated by the following equation:

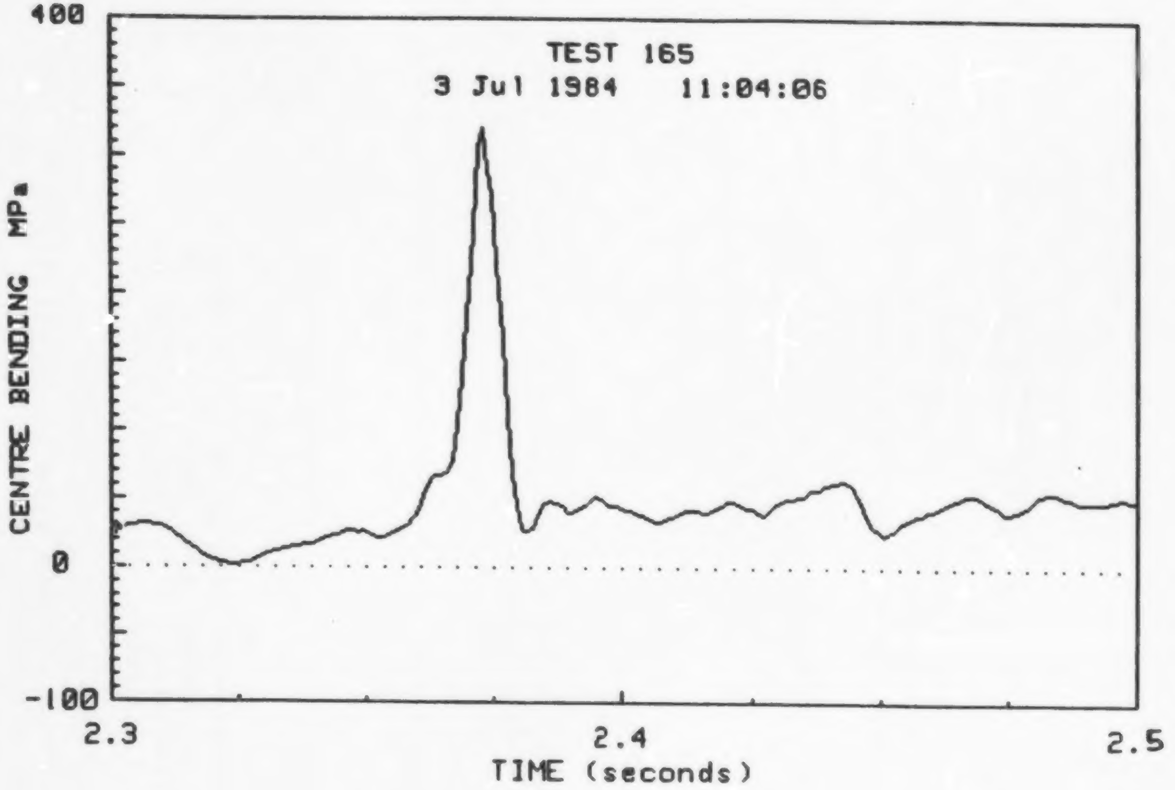
$$T = K_1(\theta_2 - \theta_1)$$

Where: $T$ = Torque on shaft,
$K_1$ = Torsional stiffness of shaft;
$\theta_1$ = Twist at propeller blade, and;
$\theta_2$ = Twist at gear wheel.

The free vibration equation of this model was solved. The two lowest natural frequencies computed by M.A.K.'s (the engine manufacturer) torsional vibration analysis (Ref 10.2), agreed with those computed from the three degrees of freedom model. The value of these frequencies are approximately the same as those estimated from full scale data. The detailed development of the model is in Appendix H.

| | Full Scale Data | Model | M.A.K.'s Model |
|---|---|---|---|
| First Natural Frequency | 4.17 Hz | 3.58 Hz | 3.85 Hz |
| Second Natural Frequency | 16.7 Hz | 13.89 Hz | 13.83 Hz |
| Third Natural Frequency | - | 42.27 Hz | 27.12 Hz |
| Fourth Natural Frequency | - | - | 44.12 Hz |

The solution for the equation of motion for the torsional response of the model to any form of torque input to the propeller blade is computed and plotted by a program developed for the H.P. 9845B desk top computer. The shape of the centre blade bending signal is used as the shape of the torque input for the model (see Figure 10.2.2A and Figure 10.2.2B). The measured response of the shafting, shown in Figures 10.2.3A and 10.2.3B, corresponds well with the predicted response shown in Figures 10.2.4A and 10.2.4B.

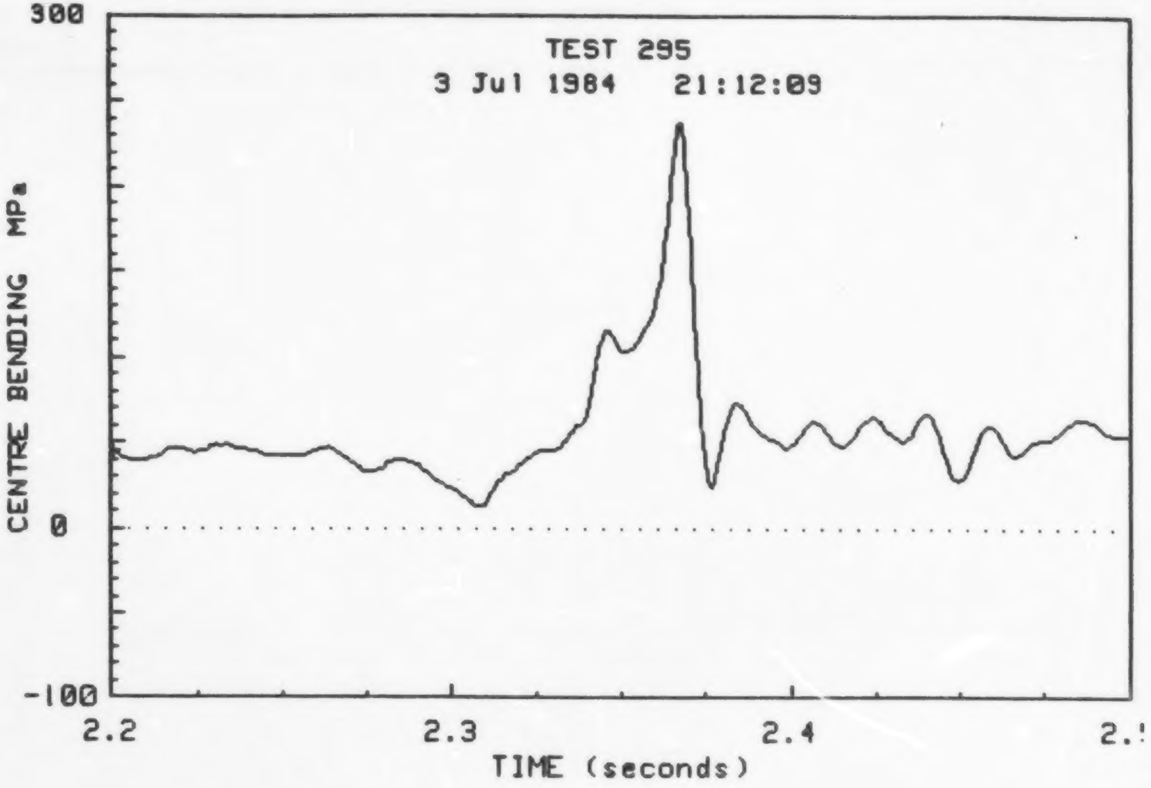


**CANADIAN MARINE DRILLING LIMITED**

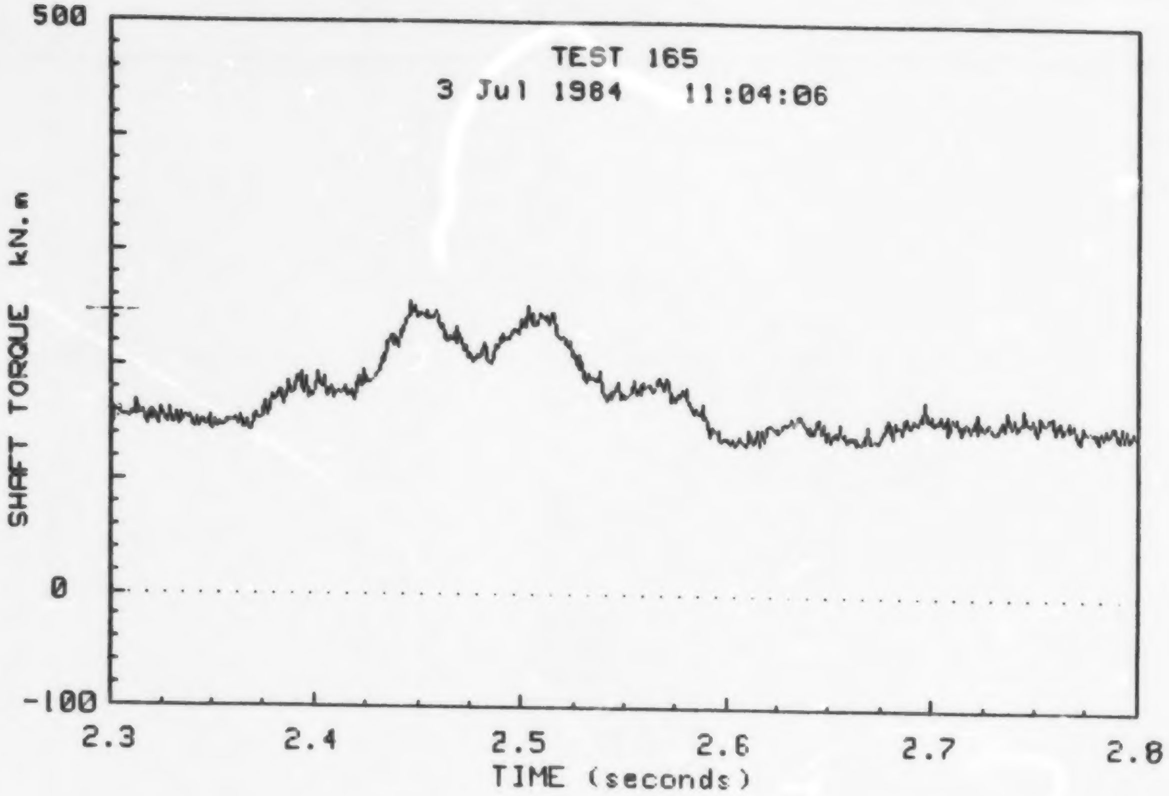
**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** TEST 165 - CENTRE BLADE BENDING SIGNAL WAVEFORM

**FIGURE No.** 10 · 2 · 2A



| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: TEST 295 - CENTRE BLADE BENDING SIGNAL WAVEFORM |
| | | FIGURE No. 10 · 2 · 2B |

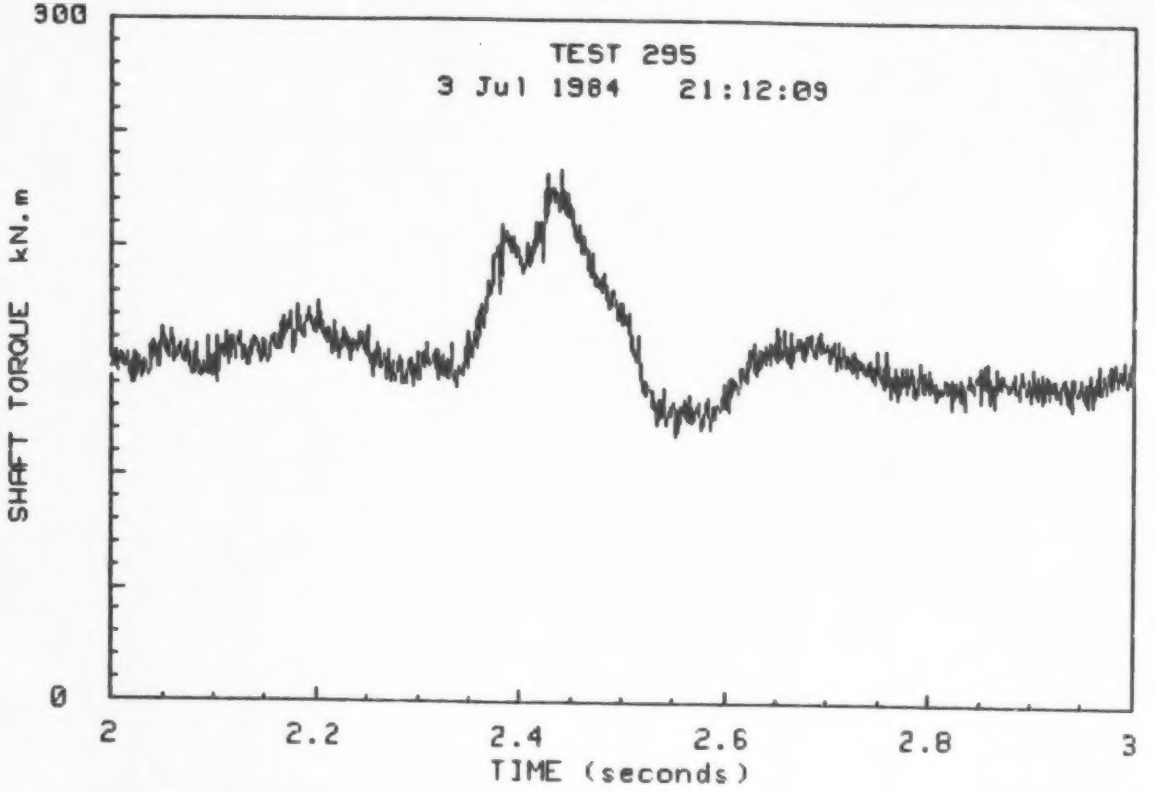


**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** **TEST 165 - MEASURED SHAFT TORQUE WAVEFORM**

**FIGURE No.** 10·2·3A



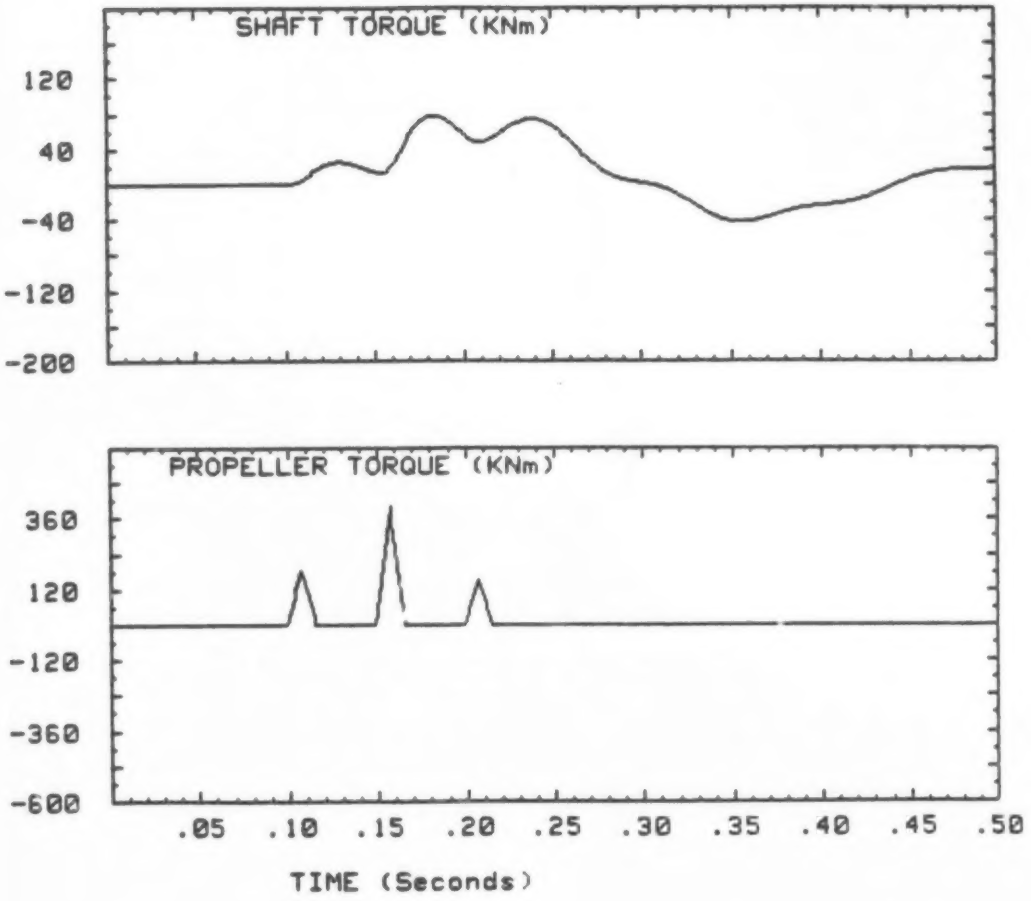
**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:** TEST 295 - MEASURED SHAFT TORQUE WAVEFORM

**FIGURE No.** 10·2·3B

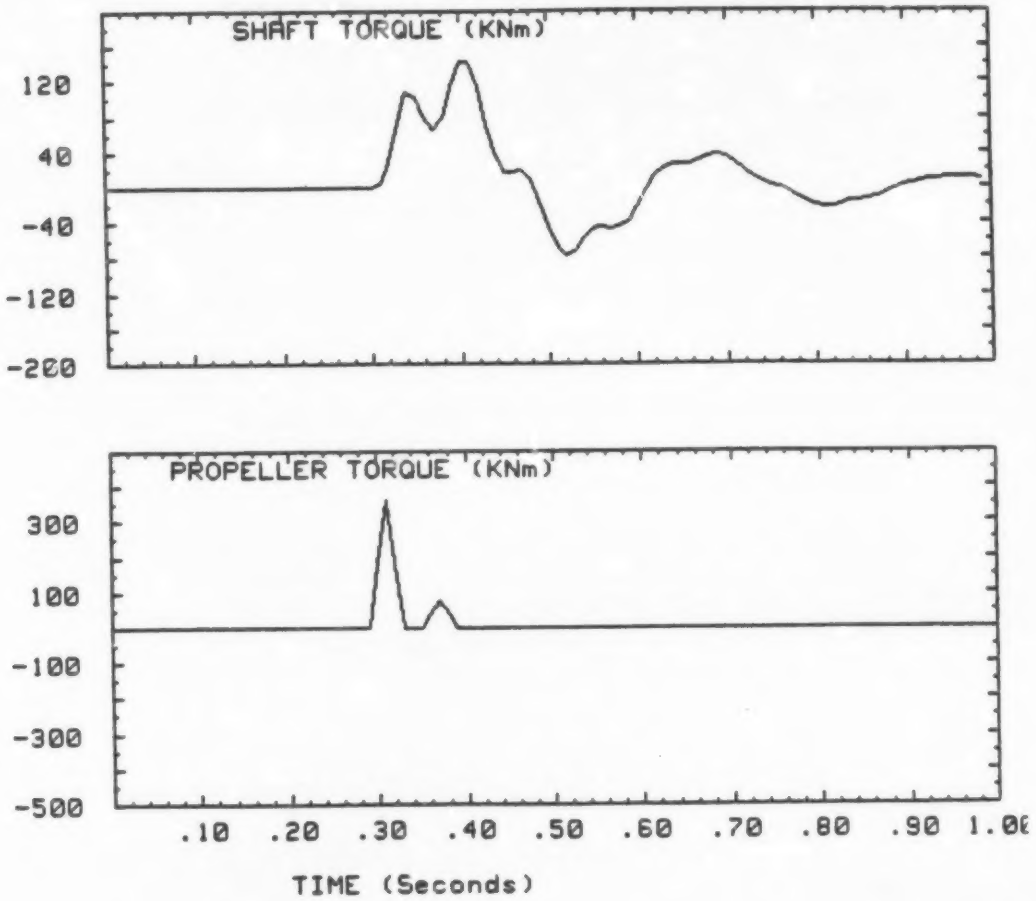
TEST 165
ANALYSIS DATE: 84/10/30



```
DAMPING RATIO  FOR THE SHAFT:       .08
DAMPING RATIO  FOR THE PROPELLER:  .1
TIME INCREMENT (SEC.):              .001
TIME AT FIRST IMPULSE (SEC.):       .1
LENGTH OF FIRST IMPULSE (SEC.):     .016     MAX. TORQUE (KNm):  185
TIME AT SECOND IMPULSE (SEC.):      .15
LENGTH OF SECOND IMPULSE (SEC.):    .016     MAX. TORQUE (KNm):  400
TIME AT THIRD IMPULSE (SEC.):       .2
LENGTH OF THIRD IMPULSE (SEC.):     .016     MAX. TORQUE (KNm):  150
```

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: TORQUE FOR LEMEUR PROPULSION SYSTEM MODEL TEST 165<br>FIGURE No. 10·2·4A |

TEST 295
ANALYSIS DATE: 84/10/30



DAMPING RATIO FOR THE SHAFT: .08
DAMPING RATIO FOR THE PROPELLER: .1
TIME INCREMENT (SEC.): .01
TIME AT FIRST IMPULSE (SEC.): .3
LENGTH OF FIRST IMPULSE (SEC.): .04 MAX. TORQUE (KNm): 360
TIME AT SECOND IMPULSE (SEC.): .36
LENGTH OF SECOND IMPULSE (SEC.): .04 MAX. TORQUE (KNm): 75

| CANADIAN MARINE DRILLING LIMITED | MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS | TITLE: TORQUE FOR LEMEUR PROPULSION SYSTEM MODEL TEST 295<br>FIGURE No. 10·2·4B |
|---|---|---|

## 10.3 Longitudinal Model

The longitudinal model is shown in Figure 10.3.1. The solution for the response of the model to thrust inputs on the propeller is derived by using the model superposition technique also. The equation of motion of the propulsion model is:

$$[M][\ddot{X}] + [G_L][\dot{X}] + [C_L][\dot{X}] + [K_T][X] = [F_L]$$

Where:
$[M]$ = Mass matrix;
$[G_L]$ = Shaft damping matrix (proportional to $[K_L]$);
$[C_L]$ = Propeller damping matrix (only one non-zero element);
$[K_L]$ = Longitudinal stiffness matrix;
$[F_L]$ = Force matrix (thrust on propeller), and;
$[X]$ = Movement of shaft at each node.

The longitudinal movement of the shaft at each node is solved for each point in time. The thrust on the shaft where the gauges are located is then calculated by the following equation:

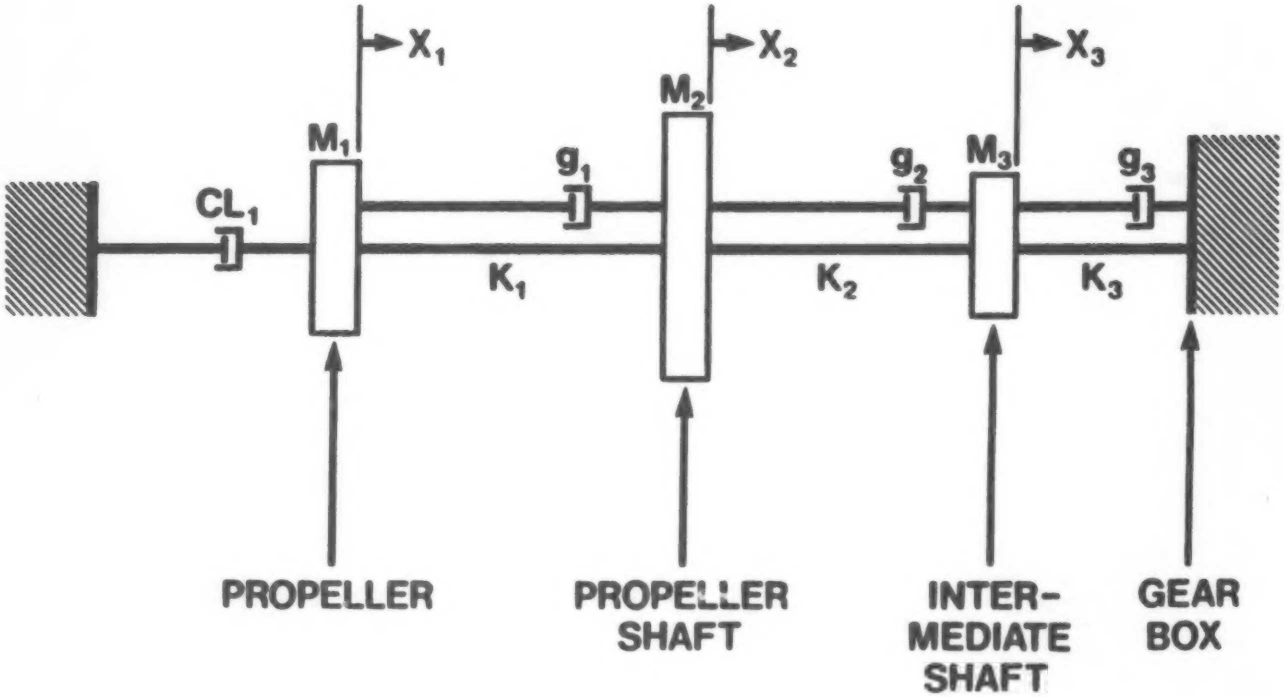
$$F = -(K_3)(X_3)$$

Where:
$F$ = Thrust on shaft;
$K_3$ = Longitudinal stiffness of shaft,
and;
$X_3$ = Movement of shaft aft of gauges.

The free vibration equations of this model were solved. The natural frequencies computed and estimated from full scale data are as follows:

|  | Model | Full Scale Data |
|---|---|---|
| First Natural Frequency | 25.5 Hz | 25 Hz |
| Second Natural Frequency | 76.1 Hz | not available |
| Third Natural Frequency | 106 Hz | not available |

The shape of the centre bending signal is used as


X₁
X₂
X₃
M₁
M₂
M₃
g₁
g₂
g₃
CL₁
K₁
K₂
K₃
PROPELLER
PROPELLER SHAFT
INTER-MEDIATE SHAFT
GEAR BOX

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE-PROPELLER<br>INTERACTION PARAMETERS | TITLE: ROBERT LEMEUR<br>LONGITUDINAL MODEL<br>FIGURE No. 10·3·1 |

the shape of the thrust input for the model (see Figure 10.2.2A and 10.2.2B). The response of the model is computed and plotted by a program similar to the torsional response program. The response of the model shown in Figure 10.3.2 approximates the measured response shown in Figure 10.3.3.

During the time period from the start of the response until the peak, both model outputs are approximately the same as the measured response. After this period, various parameters changed (propeller pitch, fuel rack, propeller-ice interaction), resulting in some discrepancy in the last part of the model's response waveform. When more than one blade hits the ice, the same shape of the model input force or torque is assumed for the subsequent hits.

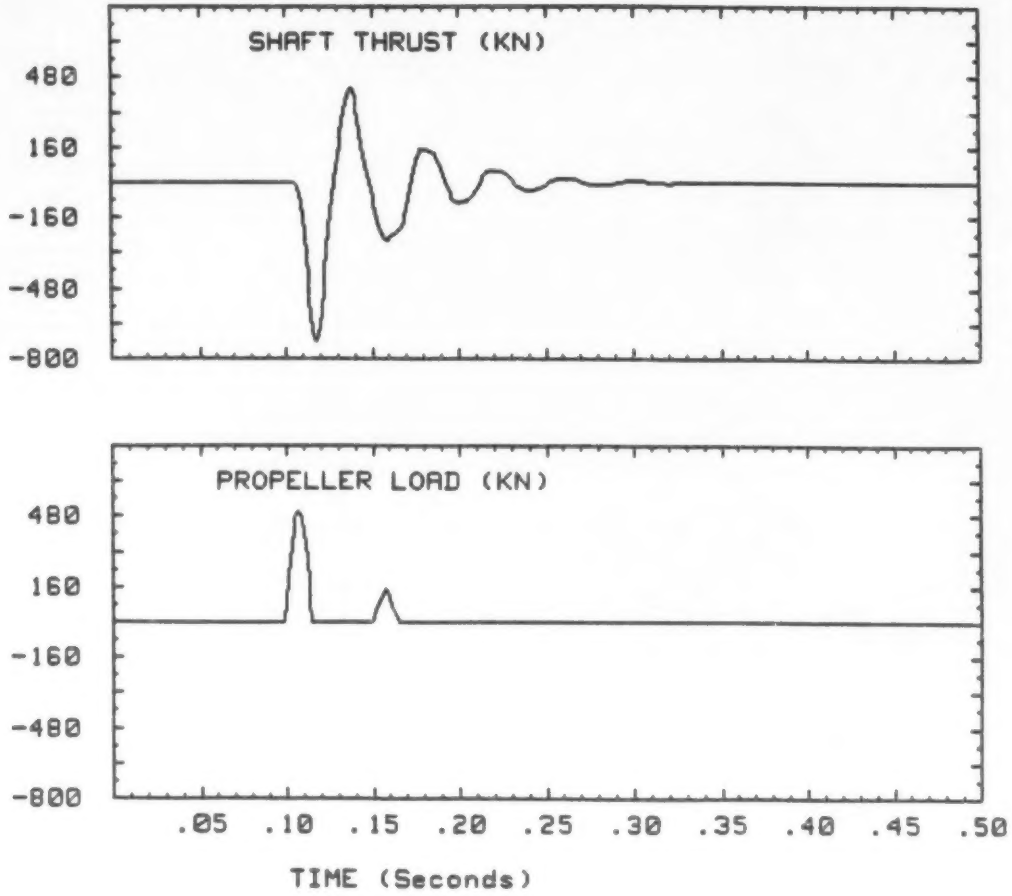
### 10.4 Conclusions

- The models developed are in good agreement with the real system, as determined by comparing theoretical responses versus measured responses.

- The models will be a useful tool in helping to estimate the magnitude and direction of ice loads on the propeller. This is not possible with actual measurements due to the inability to measure the in plane blade force.

- For short duration impacts, the models help determine the number of blades that hit the ice, as given by the theoretical impact force time history required to produce the chosen shaft torsional and longitudinal responses.

TEST 165
ANALYSIS DATE: 84/10/30



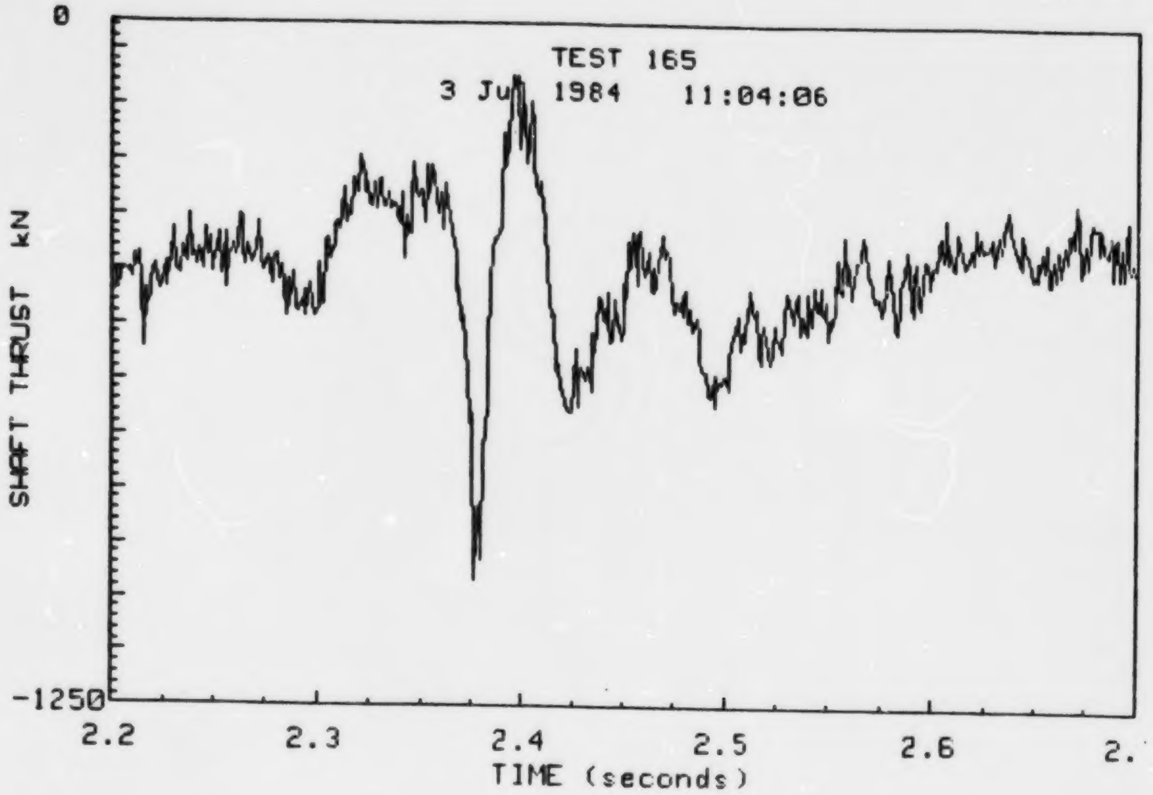
| | | | |
|---|---|---|---|
| DAMPING COEFFICIENT FOR SHAFT: | .08 | | |
| DAMPING COEFFICIENT FOR PROP.: | .08 | | |
| TIME INCREMENT: | .001 | | |
| TIME AT FIRST IMPULSE (SEC.) | .1 | | |
| LENGTH OF FIRST IMPULSE (SEC.) | .016 | MAX. PROPELLER LOAD (KN): | 500 |
| TIME AT SECOND IMPULSE (SEC.) | .15 | | |
| LENGTH OF SECOND IMPULSE (SEC.) | .016 | MAX. PROPELLER LOAD (KN): | 150 |

**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE: THRUST FOR LEMEUR PROPULSION SYSTEM MODEL TEST 165**

**FIGURE No. 10 · 3 · 2**



CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

TITLE: TEST 165 - MEASURED SHAFT THRUST WAVEFORM

FIGURE No. 10·3·3

## 11. CONCLUSIONS

This report addresses a number of the stated objectives of the project namely:

- While the vessel was in open water and in heavy ice conditions data was obtained from the instrumented propeller blade. A physical calibration procedure of the propeller blade was also performed which should enable estimates of ice interaction forces to be made from the collected data.
- A digital data acquisition and analysis system, capable of near-real-time data selection and analysis, was designed, constructed and proven during the intensive field test program.
- Simple analytical models of the propulsion system to describe the various aspects of the ice interaction phenomena were developed and presented.
- Ice condition data was collected and interpreted.

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# APPENDIX A

# DATA ON THE MV ROBERT LEMEUR

## APPENDIX A - DATA ON ROBERT LEMEUR

### Ship:

| | |
|---|---|
| Length Overall | 82.8 m |
| Breadth Moulded | 18.0 m |
| Ice breaking Draft | 5.5 m |
| Deadweight | 2690.4 tonnes |

### Propulsion:

| | |
|---|---|
| Engine | M.A.K. 12M453V - two of |
| Engine Power at M.C.R. | 3530 kW |
| Clutch | L&S Pneumaflex KA320MD - two of |
| Gearbox | L&S GCE8505 - two of |

### Propellers:

| | |
|---|---|
| LIPS | CPP |
| Hub Type | 4C115W |
| Number of Blades | 4 |
| Propeller Speed | 209 rpm |
| Hub to Prop. Dia. Ratio | 0.367 |
| Propeller Diameter | 3.0 m |
| Mass of Blade w/o Foot | 452 kg (C.O.G.- 0.947 m) |
| Mass of Blade w/ Foot | 615 kg (C.O.G.- 0.819 m) |
| Blade Material | Cunial Bronze |
| Ultimate | 647 MPa |
| Yield | 260 MPa |
| elongation | 20% |

### Nozzle:

| | |
|---|---|
| Nozzle Inside Diameter | 3.03 m |
| Nozzle Length | 1.4 m |
| Length to Prop. Dia. Ratio | 0.4667 |

# APPENDIX B
# COMPUTER HARDWARE LISTING

# COMPUTER HARDWARE LISTING

Computer: Hewlett Packard HP 9836A with monochrome monitor

Memory Requirements: 2 Mbyte

Language System: Hewlett Packard Extended Basic Version 2.1

Peripheral:
-Printer - Hewlett Packard HP9876A;
-Nine Track Tape Drive - Innovative Data Technology GPIB1050, and;
-Two of HPIB cables

# APPENDIX C
# LISTING OF DATA ACQUISITION PROGRAM FOR ON-BOARD TESTS

## PROGRAM "RLDAR-7"

The data acquisition system used on-board the vessel during the June/July 1984 test period controls the operation of the HP6940B analogue subsystem and stores data in a 1.5 Mbyte buffer. On receipt of a trigger signal stores 7,000 readings of each of 18 channels on 5 1/4" floppy disks. Disks are readable by program "ANALYZE" and has utility function for inspection of acquired data, displayed in volts.

```
1000 ! Program RLDAR7 /M. H. Edgecombe /84-05-17
1010 ! High Speed Data Acquisition Routine for the HP 9836 desktop computer
1020 ! and the HP 6940B multiprogrammer.
1030 !
1040 ! Hardware Configuration:
1050 !      - 1 of HP Series 200 model 36 desktop computer (HP 9836)
1060 !      - 6 of HP 98256 256K RAM memory boards installed in the 9836
1070 !      - 1 of HP 98622A opt. 003 GP-IO interface (select code 12)
1080 !
1090 !      - 1 of HP 6940B multiprogrammer mainframes connected to the HP9836
1100 !        via the HP 98622A GP-IO interface and opt. 003 cable.
1110 !      - 1 of HP 69351B voltage regulator card installed in m/p slot 600
1120 !      - 1 of HP 69602A timer/pacer card installed in m/p slot 400
1130 !      - 1 of HP 69422A high speed a/d card installed in m/p slot 401
1140 !      - 2 of HP 69336B high speed scanner cards installed in m/p slots 402
1150 !        and 403
1160 !
1170 ! Operating System and Extensions:
1180 !      - BASIC 2.0
1190 !      - BASIC Extensions 2.1
1200 !
1210   OPTION BASE 1
1220   PRINTER IS 1
1230   PRINT CHR$(12)
1240 !
1250 Ram_check:  !
1260   ON ERROR GOTO Ram_error
1270   ASSIGN @Temp TO "TEMP:MEMORY,0,7"
1280   OFF ERROR
1290   GOTO Declare_storage
1300 !
1310 Ram_error:  !
1320   IF ERRN<>56 AND ERRN<>76 THEN
1330      DISP ERRM$
1340      PAUSE
1350      GOTO Ram_check
1360   END IF
1370 !
1380   IF ERRN=76 THEN PRINT "ISSUE:  INITIALIZE "":MEMORY,0,7"",1000"
1390   IF ERRN=56 THEN
1400   PRINT "ISSUE:  CREATE BDAT ""TEMP:MEMORY,0,7"",986 THEN CONTINUE"
1410   END IF
1420   PAUSE
1430   GOTO Ram_check
1440 !
1450 Declare_storage:  !
1460   INTEGER I,J,K,L,M,N,Nchnls,Range
1470   INTEGER Period,Form,Lines,Start_line,Int_status,Int_buffer,Int_trigger
1480   INTEGER V(7000,18),A(7000,18)
1490   DIM Title$[80],Date$[12],Time$[12],Sig$(2,18)[9],Id$(18)[7],File$[30]
1500   DIM Yminn(18),Ymaxn(18)
1510 !
1520   ASSIGN @Buffer TO BUFFER [1572840];WORD
1530   ASSIGN @Multiprogrammer TO 12;WORD
1540   ASSIGN @Trigger TO 13;WORD
1550 !
1560   Nchnls=18
1570   Rdgs=7000
1580   Words=Rdgs*Nchnls
1590   Bytes=Words*2
1600   Dma_length=131072      ! 128*1024
1610   Disk_length=Bytes
1620   Buffer_length=1572840 ! 6*256*1024-24
1630   Auto_flag=0
1640   MAT V= (-1)
1650 !
```

```
1660   DATA "  CENTRE "," BENDING ","CEB",-5,5
1670   DATA "    TE   ","  TORQUE ","TEQ",-5,5
1680   DATA "    LE   "," BENDING ","LEB",-5,5
1690   DATA "  CENTRE ","  TORQUE ","CEQ",-5,5
1700   DATA "    TE   "," BENDING ","TEB",-5,5
1710   DATA "    LE   ","  TORQUE ","LEQ",-5,5
1720   DATA " SLIDING ","  BLOCK  ","SBF",-5,5
1730   DATA "  SHAFT  ","  THRUST ","THRUST",-1,1
1740   DATA "  SHAFT  ","  TORQUE ","TORQUE",-1,1
1750   DATA "  SERVO  "," PRESSURE","SERVO",-5,5
1760   DATA " AFT PT  ","  PROBE  ","AP",-10,10
1770   DATA " AFT TOP ","  PROBE  ","AT",-10,10
1780   DATA "   FUEL  ","   RACK  ","FUEL",-10,10
1790   DATA " FWD STBD","  PROBE  ","FS",-10,10
1800   DATA "  SHAFT  ","   RATE  ","RATE",-5,5
1810   DATA "   PROP  ","  PITCH  ","PITCH",-10,10
1820   DATA "   SHIP  ","  SPEED  ","SPEED",-.1,1.5
1830   DATA "  RUDDER ","  ANGLE  ","RUDDER",-5,5
1840 !
1850   FOR I=1 TO 18
1860   READ Sig$(1,I),Sig$(2,I),Id$(I),Yminn(I),Ymaxn(I)
1870   NEXT I
1880 !
1890   Timer_card=0
1900   Ad_card=4096
1910   Scanner_card0=8192
1920   Scanner_card1=12288
1930   Cw=-4096
1940   Isl=128
1950   Dte=64
1960   Sye=32
1970   Tme=16
1980 Ctl_fmt: IMAGE #,W
1990 !
2000 Start: !
2010   GCLEAR
2020   IF TIMEDATE<2.09E+11 THEN GOSUB Set_time
2030 !
2040 Driver: !
2050   OFF KEY
2060   ON KEY 0 LABEL "START SCAN",3 GOTO Input_data
2070   ON KEY 1 LABEL "PLOT DATA",3 GOTO Graphics
2080   ON KEY 2 LABEL "SAVE DATA",3 GOTO Save_data
2090   ON KEY 3 LABEL "MANUAL SAVE",3 GOSUB Manual
2100   ON KEY 5 LABEL "ABORTIO",3 GOTO Abort_io
2110   ON KEY 6 LABEL "CONVERT",3 GOTO Convert
2120   ON KEY 7 LABEL "GET DATA",3 GOTO Get_data
2130   ON KEY 8 LABEL "AUTO SAVE",3 GOSUB Auto
2140   ON KEY 9 LABEL "",3 GOTO Idle
2150 !
2160 Idle: !
2170   GOSUB Display_time
2180   GOTO Idle
2190 !
2200 Abort_io:  !
2210   GOSUB Shut_down
2220   PRINT CHR$(12)
2230   GOTO Idle
2240 !
2250 Manual:  !
2260   Auto_flag=0
2270   BEEP
2280   RETURN
2290 !
2300 Auto:  !
2310   Auto_flag=1
```

```
2320   BEEP
2330   RETURN
2340 !
2350 Input_data: !
2360   Title$=""
2370   Date$=""
2380   Time$=""
2390   File$=""
2400   GOTO Scan
2410 !
2420 Scan:  !
2430   Range=0          ! timer increment is 10^Range microseconds
2440   Rate=10^Range*1.E-6
2450   Range=2^Range
2460   Period=27        ! time between channels is 2*Period*Range
2470   Rate=(1/(Rate*2*Period))/Nchnls
2480   Time_span=Buffer_length*.5/(Rate*Nchnls)
2490   Card0_start=15
2500   Card1_start=1
2510 !
2520   PRINT CHR$(12)
2530   PRINT "DATA ACQUISITION SEQUENCE INITIATED: "
2540   PRINT "NUMBER OF CHANNELS =";Nchnls;"  CHANNEL RATE =";
2550   PRINT USING "DDDDDD,#";Rate
2560   PRINT " READINGS/CHANNEL/SECOND"
2570   DISP CHR$(131);"ACQUIRING DATA";CHR$(128)
2580 !
2590 Reset_trigger: !
2600   STATUS 13,5;Int_status
2610   Int_status=BIT(Int_status,2)
2620   IF NOT Int_status THEN Reset_6940b
2630   BEEP
2640   DISP CHR$(130);"RESET TRIGGER";CHR$(128)
2650   GOTO Reset_trigger
2660 !
2670 Reset_6940b: !
2680   DISP
2690   ABORTIO @Multiprogrammer
2700   RESET 12
2710   RESET @Buffer
2720   OUTPUT 12 USING Ctl_fmt;Cw+Sye+Dte
2730   OUTPUT 12 USING Ctl_fmt;Timer_card+Period
2740   OUTPUT 12 USING Ctl_fmt;Timer_card+3072
2750 !
2760 Sample_rate: !
2770   OUTPUT 12 USING Ctl_fmt;Cw+Sye
2780   OUTPUT 12 USING Ctl_fmt;Timer_card+3072+Range
2790   OUTPUT 12 USING Ctl_fmt;Timer_card+Period
2800 !
2810 Start_chan: !
2820   OUTPUT 12 USING Ctl_fmt;Cw+Sye
2830   OUTPUT 12 USING Ctl_fmt;Scanner_card1+2048+Card1_start    ! 2048=disabled
2840   OUTPUT 12 USING Ctl_fmt;Scanner_card0+Card0_start         ! enabled
2850 !
2860 Address_adc: !
2870   OUTPUT 12 USING Ctl_fmt;Cw+Isl+Sye+Tme
2880   CONTROL 12,3;Ad_card
2890 !
2900 Transfer: !
2910   ON KEY 9 LABEL "TRIGGER",3 GOTO Event
2920   ENABLE
2930   T1=TIMEDATE
2940   TRANSFER @Multiprogrammer TO @Buffer;CONT
2950 !
2960 Wait: WAIT .05
2970   STATUS 13,5;Int_status
```

```
2980   STATUS 13,3;Int_data
2990   Int_status=BIT(Int_status,2)
3000   IF Int_status THEN GOTO Event
3010   GOSUB Ptrs
3020   IF Current_length<Buffer_length THEN Wait
3030   DISABLE
3040   GOTO Reset_6940b
3050 !
3060 Event: !
3070   DISABLE
3080   T2=TIMEDATE
3090   Tp=Buffer_length*(T2-T1)/Time_span
3100   Int_data=BINAND(Int_data,1023)
3110   PRINT
3120   PRINT "INTERRUPT DATA =";Int_data
3130 !
3140 End_loop: WAIT .1
3150   GOSUB Ptrs
3160   IF Fp<Tp+Dma_length AND Current_length<Buffer_length THEN End_loop
3170 !
3180   BEEP
3190   GOSUB Shut_down
3200   IF Current_length=Buffer_length THEN Ep=1320841
3210   Tp=36*PROUND((Tp/36),0)
3220   IF Current_length<>Buffer_length THEN Ep=MAX(1,Tp-90000+1)
3230   Offset=PROUND((Tp-Ep)/36,0)
3240   Date$=DATE$(T2)
3250   Time$=TIME$(T2)
3260   CONTROL @Buffer,5;Ep
3270   PRINT USING "13A,DDD.DDD,#";"BUFFER SPAN =";Time_span
3280   PRINT USING "10A,DDD.DDD,#";"   T2-T1 =";T2-T1
3290   PRINT USING "7A,DDDDDDD,#";"   Tp =";Tp
3300   PRINT USING "11A,DDDDDDD";"   OFFSET =";Offset
3310 !
3320   DISP CHR$(131);"WRITING DATA TO FLASH DISK";CHR$(128)
3330   ASSIGN @Temp TO "TEMP:MEMORY,0,7"
3340   TRANSFER @Buffer TO @Temp;COUNT Disk_length,WAIT
3350   ASSIGN @Temp TO *
3360   ASSIGN @Infile TO "TEMP:MEMORY,0,7"
3370   ENTER @Infile;V(*)
3380   ASSIGN @Infile TO *
3390 !
3400   PRINT
3410   PRINT "END OF DATA ACQUISITION SEQUENCE"
3420   PRINT "TRIGGER RECEIVED AT "&Time$
3430   IF Auto_flag=1 THEN GOTO Auto_save
3440 !
3450 Convert: !
3460   DISP CHR$(131);"DATA CONVERSION EXECUTING";CHR$(128)
3470   MAT V= V+(32767)
3480   MAT V= V+(1)
3490   MAT A= (2047)
3500   MAT A= V>A
3510   MAT A= A*(-4096)
3520   MAT V= V+A
3530 !
3540   BEEP
3550   PRINT
3560   PRINT "DATA CONVERSION COMPLETE"
3570   ENABLE
3580   GOTO Driver
3590 !
3600 Shut_down: !
3610   ABORTIO @Multiprogrammer
3620   OUTPUT 12 USING Ctl_fmt;Cw+Sye+Dte
3630   OUTPUT 12 USING Ctl_fmt;Timer_card+Period
```

```
3640   OUTPUT 12 USING Ctl_fmt;Timer_card+3072
3650   RETURN
3660 !
3670 Ptrs:  !
3680   STATUS @Buffer,3;Fp
3690   STATUS @Buffer,4;Current_length
3700   STATUS @Buffer,5;Ep
3710   DISP USING "1A,3(DDDDDDDD,3X),1A";CHR$(129),Ep,Current_length,Fp,CHR$(128
)
3720   RETURN
3730 !
3740 Graphics: !
3750   GCLEAR
3760   Channel$="1"
3770   Xmn=0
3780   Xmx=Rdgs/Rate
3790 !
3800 G_loop:  !
3810   OFF KNOB
3820   INPUT "IDENTIFICATION OF CHANNEL TO BE PLOTTED ...",Channel$
3830   GOSUB Find_channel
3840   IF Sig=-1 THEN GOTO G_loop
3850 !
3860   Ymin=Yminn(Sig)
3870   Ymax=Ymaxn(Sig)
3880 !
3890 Enter_ylimits:   INPUT "ENTER YMIN,YMAX...",Ymin,Ymax
3900   IF Ymin>Ymax THEN
3910     BEEP
3920     GOTO Enter_ylimits
3930   END IF
3940   IF Ymin<-10.25 THEN Ymin=-10.25
3950   IF Ymax>10.25 THEN Ymax=10.25
3960 !
3970 Enter_xlimits:   INPUT "ENTER XMIN,XMAX...",Xmn,Xmx
3980   IF Xmn<0 OR Xmn>Xmx THEN
3990     BEEP
4000     GOTO Enter_xlimits
4010   END IF
4020   IF Xmx>Rdgs/Rate THEN Xmx=Rdgs/Rate
4030   Yminn(Sig)=Ymin
4040   Ymaxn(Sig)=Ymax
4050   Xmin=Rate*Xmn
4060   Xmax=Rate*Xmx
4070 !
4080   PRINT CHR$(12)
4090   OFF KEY
4100   ON KEY 0 LABEL "New Plot",3 GOTO G_loop
4110   ON KEY 1 LABEL "LABEL UP",3 GOTO Label_up
4120   ON KEY 4 LABEL "",3 GOTO G_idle
4130   ON KEY 5 LABEL "New Signal",3 GOTO New_signal
4140   ON KEY 6 LABEL "LABEL DOWN",3 GOTO Label_down
4150   ON KEY 7 LABEL "",3 GOTO G_idle
4160   ON KEY 8 LABEL "",3 GOTO G_idle
4170   ON KEY 9 LABEL "EXIT",3 GOTO Exit
4180   GOSUB Plot
4190 !
4200 G_idle:  !
4210   GOTO G_idle
4220 !
4230 Cursor_update:  !
4240   GOSUB Cursor
4250   X=PROUND(((X+KNOBX) MOD (Xmax-Xmin)),0)
4260   IF X<1 THEN X=(Xmax-Xmin)+X
4270   Y=V(Xmin+X,Sig)*.005
4280   GOSUB Cursor
```

```
4290   Yd=Y
4300   IF ABS(Yd)>999 THEN Yd=SGN(Yd)*999
4310   DISP USING "7X,1A,DDDDDD,2X,MDDD.DDD,1A";CHR$(129),Xmin+X,Yd,CHR$(128)
4320   RETURN
4330 !
4340 Label_up:  !
4350   MOVE X,Y+Yc
4360   DRAW X,Y+4*Yc
4370   MOVE X,Y+5*Yc
4380   LORG 2
4390   LDIR 90
4400   LABEL USING "K";Y
4410   GOTO G_idle
4420 !
4430 Label_down:  !
4440   MOVE X,Y-Yc
4450   DRAW X,Y-4*Yc
4460   MOVE X,Y-5*Yc
4470   LORG 8
4480   LDIR 90
4490   LABEL USING "K";Y
4500   GOTO G_idle
4510 !
4520 Exit:  GCLEAR
4530        OFF KNOB
4540   GOTO Driver
4550 !
4560 New_signal: OFF KNOB
4570   INPUT "IDENTIFICATION OF CHANNEL TO BE PLOTTED...",Channel$
4580   GOSUB Find_channel
4590   IF Sig=-1 THEN GOTO New_signal
4600   GOSUB Plot_wave_form
4610   GOTO G_idle
4620 !
4630 Plot:  !
4640   DEG
4650   GINIT
4660   GRAPHICS ON
4670   FRAME
4680   VIEWPORT 15,130,15,95
4690   WINDOW Xmin,Xmax,Ymin,Ymax
4700   Xc=.01*(Xmax-Xmin)
4710   Yc=.013*(Ymax-Ymin)
4720 !
4730   IF (Xmax-Xmin)<=.4*Rate THEN
4740     Xspace=.01*Rate
4750     Xcount=10
4760     END IF
4770   IF (Xmax-Xmin)>.4*Rate AND (Xmax-Xmin)<=4.0*Rate THEN
4780     Xspace=.1*Rate
4790     Xcount=10
4800     END IF
4810   IF (Xmax-Xmin)>4.0*Rate THEN
4820     Xspace=.1*Rate
4830     Xcount=10
4840     END IF
4850   IF (Ymax-Ymin)<=.4 THEN
4860     Yspace=.005
4870     Ycount=20
4880     END IF
4890   IF (Ymax-Ymin)>.4 AND (Ymax-Ymin)<=4.0 THEN
4900     Yspace=.10
4910     Ycount=10
4920     END IF
4930   IF (Ymax-Ymin)>4.0 THEN
4940     Yspace=1
```

```
4950    Ycount=1
4960    END IF
4970   AXES Xspace,Yspace,Xmin,0,Xcount,Ycount
4980 !
4990   LDIR 0
5000   LORG 3
5010   CSIZE 3.5
5020   MOVE Xmin+.01*(Xmax-Xmin),-.015*(Ymax-Ymin)
5030   LABEL USING "DD.DD";Xmin/Rate
5040   LORG 9
5050   MOVE Xmax,-.015*(Ymax-Ymin)
5060   LABEL USING "DD.DD";Xmax/Rate
5070 !
5080   CLIP OFF
5090   LORG 5
5100   MOVE Xmin+.5*(Xmax-Xmin),-.05*(Ymax-Ymin)
5110   LABEL USING "K";"TIME (seconds)"
5120 !
5130   LORG 8
5140   MOVE Xmin-.015*(Xmax-Xmin),Ymin
5150   LABEL USING "K";Ymin
5160   MOVE Xmin-.015*(Xmax-Xmin),Ymax
5170   LABEL USING "K";Ymax
5180 !
5190   LDIR 90
5200   LORG 4
5210   MOVE Xmin-.06*(Xmax-Xmin),Ymin+.5*(Ymax-Ymin)
5220   LABEL USING "K";Sig$(1,Sig)&Sig$(2,Sig)&" (volts)"
5230 !
5240   LDIR 0
5250   LORG 4
5260   MOVE Xmin+.5*(Xmax-Xmin),Ymax
5270   LABEL USING "K";Title$[1,50]
5280   MOVE Xmin+.5*(Xmax-Xmin),Ymin+.95*(Ymax-Ymin)
5290   IF LEN(Title$)>50 THEN LABEL USING "K";Title$[51,80]
5300   LORG 5
5310 !
5320   MOVE Xmin+.5*(Xmax-Xmin),Ymin+.95*(Ymax-Ymin)
5330   LABEL USING "K";Time$&"  "&Date$
5340   CLIP ON
5350 !
5360 Plot_wave_form:  !
5370   I=MAX(1,Xmin)
5380   MOVE I,V(I,Sig)*.005
5390   IF Xmax>Rdgs THEN Xmax=Rdgs
5400   FOR I=I TO Xmax
5410      PLOT I,V(I,Sig)*.005,-1
5420   NEXT I
5430 !
5440   X=1
5450   Y=V(Xmin+X,Sig)*.005
5460   GOSUB Cursor
5470   ON KNOB .1 GOSUB Cursor_update
5480   RETURN
5490 !
5500 Cursor:  !
5510   PEN 0
5520   MOVE Xmin+X-Xc,Y
5530   DRAW Xmin+X+Xc,Y
5540   MOVE Xmin+X,Y-Yc
5550   DRAW Xmin+X,Y+Yc
5560   PEN 1
5570   RETURN
5580 !
5590 Save_data:  !
5600   DISP Time$,Date$;
```

```
5610   INPUT "  ENTER NAME OF OUTPUT DATA FILE...",File$
5620   INPUT "  ENTER TEST TITLE (60 char. max.)...",Title$
5630   Title$=File$&"  "&Title$
5640   Rec=INT((20+20+2+10+10+Rdgs*Nchnls*2+20)/256)+1
5650   CREATE BDAT File$,Rec
5660   ASSIGN @Outfile TO File$
5670   OUTPUT @Outfile;Title$,Date$,Time$,Nchnls,Rdgs,Rate,Int_data,Offset,V(*)
5680   ASSIGN @Outfile TO *
5690   GOTO Driver
5700 !
5710 Auto_save:  !
5720   File$="PROPDATA"
5730   Rec=INT((20+20+2+10+10+Rdgs*Nchnls*2+20)/256)+1
5740   ON ERROR GOSUB Second_drive
5750   CREATE BDAT File$,Rec
5760   OFF ERROR
5770   DISP CHR$(131);"SAVING DATA TO DISK";CHR$(128)
5780   ASSIGN @Outfile TO File$
5790   OUTPUT @Outfile;Title$,Date$,Time$,Nchnls,Rdgs,Rate,Int_data,Offset,V(*)
5800   ASSIGN @Outfile TO *
5810   GOTO Scan
5820 !
5830 Second_drive:  !
5840   IF ERRN=54 OR ERRN=80 THEN
5850   IF POS(File$,":INTERNAL,4,1")<>0 THEN Insert_disk
5860   File$=File$&":INTERNAL,4,1"
5870   RETURN
5880   ELSE
5890   DISP ERRM$
5900   PAUSE
5910   RETURN
5920   END IF
5930 !
5940 Insert_disk:  !
5950   DISP "INSERT EMPTY DISK VOLUME, THEN ENTER CONTINUE..."
5960   File$="PROPDATA"
5970   PAUSE
5980   RETURN
5990 !
6000 Get_data:  !
6010   File$="PROPDATA"
6020   INPUT "ENTER NAME OF DATA FILE TO BE READ...",File$
6030   ASSIGN @Infile TO File$
6040   ENTER @Infile;Title$,Date$,Time$,Nchnls,Rdgs,Rate,Int_data,Offset,V(*)
6050   ASSIGN @Infile TO *
6060   GOTO Driver
6070 !
6080 Set_time:  !
6090   INPUT "ENTER CURRENT DATE (DD MMM YYYY)...",Date$
6100   INPUT "ENTER CURRENT TIME (HH:MM:SS)...",Time$
6110   SET TIMEDATE DATE(Date$)+TIME(Time$)
6120   RETURN
6130 !
6140 Display_time:  !
6150   DISP TIME$(TIMEDATE),DATE$(TIMEDATE)
6160   RETURN
6170 !
6180 Find_channel:  !
6190   Channel$=UPC$(Channel$)
6200   FOR I=1 TO Nchnls
6210   IF Channel$=Id$(I) THEN Found
6220   IF Channel$=VAL$(I) THEN Found
6230 Next_chnl_id:   NEXT I
6240   Sig=-1
6250   RETURN
6260 Found:   Sig=I
```

```
6270   RETURN
6280   END
```

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE:<br>"RLDAR-7" |
| | | APPENDIX C |

# APPENDIX D

# COMPUTER LISTING OF PROGRAM TO CALCULATE THE [A] MATRIX

PROGRAM "MATRIX TEST"

The program uses the static calibration data obtained on the propeller blade and calculates the value of the [A] matrix.

It has functions to allow user to select which subset of the data to include in the calibration of the [A] matrix. It can display accuracy information for in-plane bending, out-of-plane bending, spindle torque, force and location. It can calculate [A] matrix of 6, 5 or 4 strain gauges active.

```
10     !
20     !    PROGRAM TO FIND THE 'A' MATRIX FOR THE PROPELLER BLADE
30     !
40     !    WRITTEN BY: DOUG MONTGOMERY
50     !    DATE: APRIL 5, 1984
60     !    VERSION: 1.00
70     !
80     !    MODIFIED BY:PAUL SPENCER
90     !    DATE:MAY 15 1984
100    !    VERSION:1.01
110    !    REASON:CASE 5&6 G1 NEGATIVE OF CASE 1 TO 4 G1 LINE 4820 ADDED (READ_D
ATA) TRCF CONECTED UP GAUGE BACKWARDS IN DOCK TRIALS
120    !
130    !    MODIFIED BY :
140    !    DATE:
150    !    VERSION:
160    !    REASON:
170       OPTION BASE 1
180       DEG
190    !
200       REAL Y(400)                              ! ONE OF FOUR FORCE VECTORS
210       REAL Y_fit(400)                          ! CALCULATED FORCE VECTOR
220       REAL Mp(400)                             ! IN-PLANE BENDING MOMENT
230       REAL Ft(400)                             ! BENDING AND TORQUE FORCE
240       REAL M(400)                              ! OUT-PLANE BENDING MOMENT
250       REAL T(400)                              ! TORQUE
260       REAL Mpx(400)                            ! SUBSET OF IN-PLANE BENDING MOMENT
270       REAL Ftx(400)                            ! SUBSET OF BENDING AND TORQUE FORCE
280       REAL Mx(400)                             ! SUBSET OF OUT-PLANE BENDING MOMENT
290       REAL Tx(400)                             ! SUBSET OF TORQUE
300       REAL Mp_calc(400)                        ! CALCULATED IN-PLANE BENDING MOMENT
310       REAL Ft_calc(400)                        ! CALCULATED BENDING AND TORQUE FORCE
320       REAL M_calc(400)                         ! CALCULATED OUT-PLANE BENDING MOMENT
330       REAL T_calc(400)                         ! CALCULATED TORQUE
340       INTEGER Usage(400)                       ! SUBSET USAGE ARRAY
350       !                                   DATA READ FROM DISC FILES
360       DIM Comment$[80]                         ! COMMENT FROM DISC FILE
370       REAL Slope                               ! CALIBRATION FORCE SLOPE
380       REAL Offset                              ! CALIBRATION FORCE OFFSET
390       REAL Force_mv(40)                        ! CALIBRATION FORCE IN MILLIVOLTS
400       REAL Theta_read(40)                      ! HORIZONTAL ANGLE OF CALIBRATION
410       REAL Beta_read(40)                       ! VERTICAL ANGLE OF CALIBRATION
420       REAL R_radius(40)                        ! RELATIVE RADIUS OF CALIBRATION
430       REAL R_chord(40)                         ! RELATIVE CHORD OF CALIBRATION
440       REAL G(40,6)                             ! STRAIN GUAGE VALUES
450       !                                   LARGE ARRAYS OF ALL DISC FILE DATA
460       REAL Force(400)                          ! CALIBRATION FORCE IN KILO-NEWTONS
470       REAL Theta(400)                          ! HORIZONTAL ANGLE
480       REAL Beta(400)                           ! VERTICAL ANGLE
490       REAL Radius(400)                         ! RELATIVE RADIUS
500       REAL Chord(400)                          ! RELATIVE CHORD
510       REAL Q(400,6)                            ! STRAIN GUAGE VALUES
520       !
530       REAL Z(400,6)                            ! Q ARRAY MINUS DEAD CHANNELS
540       REAL X(400,6)                            ! Z ARRAY MINUS NOT USED DATA POINTS
550       !
560       REAL Height(400)                         ! HEIGHT AT DATA POINTS
570       REAL Rho(400)                            ! WIDTH AT DATA POINTS
580       !
590       REAL A(6)                                ! EACH LINE OF 'A' MATRIX
600       REAL A_matrix(4,6)                       ! 'A' MATRIX, FROM REGRESSION
610       REAL R(6)                                ! REDUCED FORCE DATA MATRIX
620       REAL Array(6,6)                          ! REDUCED STRAIN DATA MATRIX
630       REAL Array_inv(6,6)                      ! INVERSE OF REDUCED MATRIX
640       INTEGER Numb_terms                       ! NUMBER OF STRAIN GUAGES
650       INTEGER Numb_points                      ! NUMBER OF ROWS OF DATA
```

```
660      REAL Lamda(400)                        ! ANGLE OF TWIST OF BLADE
670      REAL C0(400)                           ! SEMI-CHORD LENGTH FOR EACH POINT
680      REAL R0                                ! BLADE LENGTH
690      REAL Z0                                ! ROOT OF BLADE
700      REAL Angle_of_twist
710      REAL Semi_chord
720      INTEGER Dead_signal(2)                 ! STRAIN GUAGES NOT FUNCTIONING
730      INTEGER Dead_count                     ! NUMBER OF DEAD STRAIN GUAGES
740      REAL H(149)                            ! BLADE OUTLINE HEIGHT ARRAY
750      REAL P(149)                            ! BLADE OUTLINE WIDTH ARRAY
760      DIM Message$[50]
770      DIM Message2$[50]
780      INTEGER Hardcopy
790      INTEGER Case_start(10)              ! POINTER IN Q ARRAY, FIRST DATA OF CASE
800      INTEGER Case_stop(10)               ! POINTER IN Q ARRAY, LAST DATA OF CASE
810      REAL Radius_limit(2)                  ! UPPER AND LOWER BOUND OF RADIUS
820      REAL Chord_limit(2)                   ! UPPER AND LOWER BOUND OF CHORD
830      REAL Radius_loop,Chord_loop
840      DIM Version_no$[5]
850      DIM Comment1$[80]
860      DIM Comment2$[80]
870    !
880      Version_no$="1.01"
890      R0=1500
900      Z0=.37*R0
910      Second_graph=0
920    !
930    !          PROGRAM MAINLINE
940    !
950      PRINTER IS 1
960      GOSUB Read_data
970      Day$=DATE$(TIMEDATE)
980      IF Day$[LEN(Day$)-1,LEN(Day$)]<>"00" THEN 1020
990      INPUT "ENTER DATE IN FORMAT DD MMM YYYY",Day$
1000     INPUT "ENTER TIME IF FORMAT HH:MM:SS",Hours$
1010     SET TIMEDATE DATE(Day$)+TIME(Hours$)
1020   !
1030     GOSUB Blade_shape
1040 The_top:    !
1050     GOSUB Usage_table
1060     GOSUB Data_shuffle
1070     GOSUB Invert_array
1080     GOSUB Build_a_matrix
1090     GOSUB Case_select
1100     GOSUB Main_softkeys
1110     Exit_loop=0
1120 Softkey_loop:    !
1130     DISP "PICK A KEY"
1140     IF NOT Exit_loop THEN Softkey_loop
1150     PRINTER IS 1
1160     PRINT CHR$(12)
1170     DISP "THATS ALL FOR NOW FOLKS"
1180     STOP
1190   !
1200 Exit_loop:    !
1210     Exit_loop=1
1220     RETURN
1230   !
1240 Main_softkeys:    !
1250     ON KEY 0 LABEL "IN-PLANE BENDING" GOSUB Inplane_bending
1260     ON KEY 1 LABEL "OUT-PLANE FORCE" GOSUB Outplane_force
1270     ON KEY 2 LABEL "OUT-PLANE BENDING" GOSUB Outplane_bend
1280     ON KEY 3 LABEL "SPINDLE TORQUE" GOSUB Spindle_torque
1290     ON KEY 4 LABEL "LOAD LOCATION" GOSUB Plot_location
1300     ON KEY 5 LABEL "A MATRIX" GOSUB Print_a_matrix
1310     ON KEY 6 LABEL "MOMENT DATA" GOSUB Print_mp
```

```
1320      ON KEY 7 LABEL "CASE SELECT" GOSUB Case_select
1330      ON KEY 8 LABEL "USAGE TABLE" GOTO The_top
1340      ON KEY 9 LABEL "EXIT" GOSUB Exit_loop
1350      RETURN
1360  !
1370 Build_a_matrix:     !
1380      DISP "BUILDING THE 'A' MATRIX"
1390      MAT A_matrix= (0)
1400      MAT Y= Mpx
1410      GOSUB Regression
1420      FOR I=1 TO Numb_terms
1430         A_matrix(1,I)=A(I)
1440      NEXT I
1450      MAT Mp_calc= Y_fit
1460  !
1470      MAT Y= Ftx
1480      GOSUB Regression
1490      FOR I=1 TO Numb_terms
1500         A_matrix(2,I)=A(I)
1510      NEXT I
1520      MAT Ft_calc= Y_fit
1530  !
1540      MAT Y= Mx
1550      GOSUB Regression
1560      FOR I=1 TO Numb_terms
1570         A_matrix(3,I)=A(I)
1580      NEXT I
1590      MAT M_calc= Y_fit
1600  !
1610      MAT Y= Tx
1620      GOSUB Regression
1630      FOR I=1 TO Numb_terms
1640         A_matrix(4,I)=A(I)
1650      NEXT I
1660      MAT T_calc= Y_fit
1670      RETURN
1680  !
1690 Inplane_bending:     !
1700      MAT Y= Mp
1710      MAT Y_fit= Mp_calc
1720      Message$="IN-PLANE BENDING MOMENT"
1730      GOSUB Plot_data
1740      RETURN
1750  !
1760 Outplane_force:     !
1770      MAT Y= Ft
1780      MAT Y_fit= Ft_calc
1790      Message$="OUT-OF-PLANE FORCE"
1800      GOSUB Plot_data
1810      RETURN
1820  !
1830 Outplane_bend:     !
1840      MAT Y= M
1850      MAT Y_fit= M_calc
1860      Message$="OUT-OF-PLANE BENDING MOMENT"
1870      GOSUB Plot_data
1880      RETURN
1890  !
1900 Spindle_torque:     !
1910      MAT Y= T
1920      MAT Y_fit= T_calc
1930      Message$="SPINDLE TORQUE"
1940      GOSUB Plot_data
1950      RETURN
1960  !
1970 Case_select:     !
```

```
1980     INPUT "ENTER CASE NUMBER TO BE EXAMINED: ",Case_no$
1990     IF Case_no$="" THEN 1980
2000     ON ERROR GOTO Case_error
2010     Case_no=VAL(Case_no$)
2020     IF Case_start(Case_no)>Case_stop(Case_no) THEN Case_not_there
2030     OFF ERROR
2040     RETURN
2050  !
2060 Case_not_there:     !
2070     DISP "NO DATA FOR THIS CASE, RE-";
2080     GOTO Case_select
2090  !
2100 Case_error:     !
2110     DISP "CASE INPUT ERROR!  ";
2120     GOTO Case_select
2130  !
2140 Usage_table:     !
2150     Comment1$=""
2160     Comment2$=""
2170     INPUT "ENTER NUMBER OF DEAD SIGNALS (0.1, OR 2)",Dead_count
2180     IF Dead_count>0 THEN INPUT "ENTER FIRST DEAD SIGNAL (1-6)",Dead_signal(
1)
2190     IF Dead_count=2 THEN INPUT "ENTER SECOND DEAD SIGNAL (1-6)",Dead_signal
(2)
2200     IF Dead_count>0 THEN Comment1$="DEAD CHANNELS: "&VAL$(Dead_signal(1))
2210     IF Dead_count=2 THEN Comment1$=Comment1$&" "&VAL$(Dead_signal(2))
2220     MAT Usage= (1)
2230     PRINT "DATA POINT SELECTION CRITERIA"
2240     Answer$=""
2250     INPUT "CASE SELECTION, BOUNDARY SELECTION OR ALL DATA (CASE, BOUND, OR
ALL)",Answer$
2260     IF Answer$[1,1]="A" OR Answer$[1,1]="a" THEN RETURN
2270     IF Answer$[1,1]="B" OR Answer$[1,1]="b" THEN GOTO Boundary
2280     IF Answer$[1,1]="C" OR Answer$[1,1]="c" THEN GOTO Select_cases
2290     BEEP
2300     GOTO 2240
2310     !
2320 Boundary:       !
2330     INPUT "ENTER LOWER BOUND OF RELATIVE RADIUS, UPPER BOUND",Radius_limit(
1),Radius_limit(2)
2340     INPUT "ENTER LOWER BOUND OF RELATIVE CHORD, UPPER BOUND",Chord_limit(1)
,Chord_limit(2)
2350     MAT SORT Radius_limit(*)
2360     MAT SORT Chord_limit(*)
2370     Comment2$=VAL$(Radius_limit(1))&"<= RADIUS <="&VAL$(Radius_limit(2))&"
   "&VAL$(Chord_limit(1))&"<= CHORD <="&VAL$(Chord_limit(2))
2380     MAT Usage= (0)
2390     FOR I=1 TO Numb_points
2400        IF (Radius(I)>=Radius_limit(1)) AND (Radius(I)<=Radius_limit(2)) AND
 (Chord(I)>=Chord_limit(1)) AND (Chord(I)<=Chord_limit(2)) THEN Usage(I)=1
2410     NEXT I
2420     RETURN
2430     !
2440 Select_cases:      !
2450     PRINT CHR$(12)
2460     PRINT TAB(10);"CASES WITH DATA AVAILABLE"
2470     FOR File=1 TO 10
2480        IF Case_start(File)<=Case_stop(File) THEN PRINT TAB(10);File
2490     NEXT File
2500     PRINT
2510     PRINT TAB(20);"CASES SELECTED"
2520     Comment2$="CASE'S SELECTED: "
2530     MAT Usage= (0)
2540     Case$=""
2550     INPUT "ENTER CASE TO BE USED (OR PRESS CONTINUE)",Case$
2560     IF Case$="" THEN No_more_select
```

```
2570      Case_no=VAL(Case$)
2580      Comment2$=Comment2$&" "&Case$
2590      PRINT TAB(20);Case_no
2600      FOR I=Case_start(Case_no) TO Case_stop(Case_no)
2610         Usage(I)=1
2620      NEXT I
2630      GOTO 2540
2640 No_more_select:        !
2650      PRINT CHR$(12)
2660      RETURN
2670  !
2680 Print_mp:     !  PRINT THE ACTUAL VS. PREDICTED TOTAL BENDING MOMENTS
2690 Mp_image:IMAGE DDD,5X,MD.DDE,7X,MD.DDE,12X,MDDD,11X,MDDD
2700      A$=""
2710      FOR File=1 TO 10
2720         IF Case_start(File)>Case_stop(File) THEN No_print
2730         PRINT
2740         PRINT "TABLE OF ACTUAL VS. PREDICTED TOTAL BENDING MOMENTS AND THEIR
 ANGLES";TAB(64);"VERSION NO: ";Version_no$
2750         PRINT TAB(5);"ACTUAL LENGTH     PRED LENGTH    ACTUAL ANGLE     PRED
 ANGLE"
2760         PRINT
2770         FOR I=Case_start(File) TO Case_stop(File)
2780            Actual_angle=ATN(Mp(I)/M(I))
2790            Pred_angle=ATN(Mp_calc(I)/M_calc(I))
2800            Actual_length=SQR(Mp(I)^2+M(I)^2)
2810            Pred_length=SQR(Mp_calc(I)^2+M_calc(I)^2)
2820            PRINT USING Mp_image;I,Actual_length,Pred_length,Actual_angle,Pre
d_angle
2830         NEXT I
2840 No_print:        !
2850      NEXT File
2860      IF A$="Y" THEN
2870         PRINT CHR$(12)
2880         GOTO 2950
2890      END IF
2900      INPUT "WOULD YOU LIKE HARDCOPY?",A$
2910      IF A$="Y" THEN
2920         PRINTER IS 701
2930         GOTO 2710
2940      END IF
2950      PRINTER IS 1
2960      RETURN
2970  !
2980 Plot_location:     !
2990  !
3000      Units$="mm"
3010      Message2$=""
3020      GINIT
3030      CSIZE 3.3
3040      WINDOW 800,-800,0,1200
3050      GCLEAR
3060      LORG 5
3070      GRAPHICS ON
3080      Message$="PREDICTED LOCATION VS. ACTUAL LOCATION (*)"
3090      Plot_exit=0
3100      GOSUB Draw_blade
3110      GOSUB Second_softkeys
3120      Total_error=0
3130      Error_count=0
3140      FOR I=Case_start(Case_no) TO Case_stop(Case_no)
3150         MOVE Rho(I),Height(I)
3160         LABEL "*"
3170         MOVE Rho(I),Height(I)
3180         DRAW T_calc(I)/Ft_calc(I),M_calc(I)/Ft_calc(I)
3190         Total_error=Total_error+SQR((Rho(I)-T_calc(I)/Ft_calc(I))^2+(Height(
I)-M_calc(I)/Ft_calc(I))^2)
3200         Error_count=Error_count+1
3210      NEXT I
3220      GOSUB Label_blade
3230 Wait5:IF NOT Plot_exit THEN Wait5
3240      GCLEAR
3250      GRAPHICS OFF
3260      GOSUB Main_softkeys
3270      RETURN
3280  !
3290 Blade_shape:     !
3300  !    CALCULATE OUTLINE OF PROPELLER BLADE
3310      DISP "CALCULATING THE PROPELLER BLADE"
3320      K=0
3330      FOR Radius_loop=.37 TO 1.01 STEP .01
3340         K=K+1
3350         Semi_chord=-6.379832E+3*Radius_loop^4+1.404775E+4*Radius_loop^3-1.14
5168E+4*Radius_loop^2+4.911295E+3*Radius_loop-5.077262E+2
3360         H(K)=Radius_loop*R0*COS(Semi_chord*180/(PI*Radius_loop*R0))-Z0
3370         P(K)=Radius_loop*R0*SIN(Semi_chord*180/(PI*Radius_loop*R0))
3380         H(150-K)=H(K)
3390         P(150-K)=-P(K)
3400      NEXT Radius_loop
3410      FOR Chord_loop=0 TO 1.05 STEP .05
3420         K=K+1
3430         H(K)=R0*COS((.5-Chord_loop)*2*Semi_chord*180/(PI*R0))-Z0
3440         P(K)=R0*SIN((.5-Chord_loop)*2*Semi_chord*180/(PI*R0))
3450      NEXT Chord_loop
3460      RETURN
3470  !
3480 Second_softkeys:     !
3490      ON KEY 0 LABEL "HARDCOPY",2 GOSUB Dump_blade
3500      OFF KEY 1
3510      OFF KEY 2
3520      OFF KEY 3
3530      ON KEY 4 LABEL "PLOT EXIT",2 GOSUB Plot_exit
3540      OFF KEY 5
3550      OFF KEY 6
3560      OFF KEY 7
3570      OFF KEY 8
3580      OFF KEY 9
3590      RETURN
3600  !
3610 Draw_blade:     !
3620  !
3630      MOVE P(1),H(1)
3640      FOR I=2 TO 148
3650         DRAW P(I),H(I)
3660      NEXT I
3670      MOVE 510,.08*R0
3680      LABEL "L.E."
3690      MOVE -510,.08*R0
3700      LABEL "T.E."
3710      PRINT CHR$(12)
3720      RETURN
3730  !
3740 Plot_data:     !
3750  !
3760      PRINT CHR$(12)
3770      Units$="%"
3780      Message2$="- % DIFFERENCE"
3790      GINIT
3800      CSIZE 3.3
3810      WINDOW 800,-800,0,1200
3820      GCLEAR
3830      LORG 5
```

```
3840     GRAPHICS ON
3850 Percent_image:IMAGE SDDDD
3860     Plot_exit=0
3870     GOSUB Draw_blade
3880     GOSUB Second_softkeys
3890     Total_error=0
3900     Error_count=0
3910     FOR I=Case_start(Case_no) TO Case_stop(Case_no)
3920        MOVE Rho(I),Height(I)
3930        LABEL "*"
3940        IF Y(I)=0 THEN No_value
3950        Percent_fit=(INT((Y_fit(I)/Y(I)-1)*100))
3960        Total_error=Total_error+ABS(Percent_fit)
3970        Error_count=Error_count+1
3980        MOVE Rho(I),Height(I)-25
3990        LABEL Percent_fit
4000 No_value:           !
4010     NEXT I
4020     GOSUB Label_blade
4030 Wait1:     !
4040     IF NOT Plot_exit THEN Wait1
4050     GCLEAR
4060     GRAPHICS OFF
4070     GOSUB Main_softkeys
4080     RETURN
4090  !
4100 Plot_exit:     !
4110     Plot_exit=1
4120     RETURN
4130  !
4140 Label_blade:     !
4150  !
4160     MOVE 0,120
4170     LABEL "* = LOAD POINT"
4180     MOVE 0,.78*R0
4190     LABEL "ACCURACY OF INFLUENCE COEFFICIENT ANALYSIS"
4200     MOVE 0,.78*R0
4210     LABEL RPT$("_",42)
4220     MOVE 0,.74*R0
4230     LABEL DATE$(TIMEDATE)&"  "&TIME$(TIMEDATE)
4240     MOVE -600,.74*R0
4250     LABEL "VERSION NO: "&Version_no$
4260     MOVE 0,.72*R0
4270     LABEL "DATA  -  "&Message$&" ";Message2$
4280     MOVE 0,.70*R0
4290     LABEL "CASE  -  "&VAL$(Case_no)
4300     MOVE 0,.68*R0
4310     LABEL "AVERAGE DIFFERENCE  -  "&VAL$(INT(Total_error/Error_count))&"  "
&Units$
4320     MOVE 0,.66*R0
4330     LABEL Comment1$
4340     MOVE 0,.64*R0
4350     LABEL Comment2$
4360     RETURN
4370 !
4380 Dump_blade:        !
4390     PRINTER IS 701
4400     DUMP GRAPHICS
4410     PRINT
4420     PRINT
4430     PRINT
4440     IF Second_graph THEN PRINT CHR$(12)
4450     Second_graph=NOT Second_graph
4460     PRINTER IS 1
4470     GOSUB Plot_exit
4480     RETURN
```

```
4490  !
4500 Read_data:     !
4510  !
4520     INPUT "PLEASE INSTALL DISC WITH CALIBRATION DATA, PRESS CONTINUE",T$
4530     J=0
4540     FOR File=1 TO 10
4550        DISP "READING DATA FILE ";File
4560        Case_start(File)=J+1
4570        File_name$="BLADE_"&VAL$(File)
4580        ON ERROR GOTO Next_file
4590        ASSIGN @Path TO File_name$
4600        OFF ERROR
4610        ENTER @Path;Comment$
4620        ENTER @Path;Slope
4630        ENTER @Path;Offset
4640        ENTER @Path;R_radius(*)
4650        ENTER @Path;R_chord(*)
4660        ENTER @Path;Force_mv(*)
4670        ENTER @Path;Theta_read(*)
4680        ENTER @Path;Beta_read(*)
4690        ENTER @Path;G(*)
4700        ASSIGN @Path TO *
4710        FOR I=1 TO 40
4720           IF R_radius(I)=0 THEN Data_done
4730           J=J+1
4740           Semi_chord=-6.379832E+3*R_radius(I)^4+1.404775E+4*R_radius(I)^3-1
.145168E+4*R_radius(I)^2+4.911295E+3*R_radius(I)-5.077262E+2
4750           C0(J)=Semi_chord
4760           Height(J)=R_radius(I)*R0*COS((.5-R_chord(I))*Semi_chord*360/(PI*R
_radius(I)*R0))-Z0
4770           Rho(J)=R_radius(I)*R0*SIN((.5-R_chord(I))*Semi_chord*360/(PI*R_ra
dius(I)*R0))
4780           R_height=(Height(J)+Z0)/R0
4790           Angle_of_twist=-4.227393E+1*R_height^3+1.202007E+2*R_height^2-1.3
07025E+2*R_height+39.221
4800           Lamda(J)=-Angle_of_twist
4810           FOR K=1 TO 6
4820           IF J>120 AND K=1 THEN G(I,K)=-G(I,K)
4830              Q(J,K)=G(I,K)
4840           NEXT K
4850           Force(J)=Force_mv(I)*Slope+Offset
4860           Theta(J)=Theta_read(I)
4870           Beta(J)=Beta_read(I)
4880           Radius(J)=R_radius(I)
4890           Chord(J)=R_chord(I)
4900         NEXT I
4910 Data_done:     !
4920         Case_stop(File)=J
4930 Next_file:        !
4940      NEXT File
4950      Numb_points=J
4960  !
4970      FOR I=1 TO Numb_points
4980         Ft(I)=Force(I)*SIN(Lamda(I)-Theta(I))*COS(Beta(I))
4990         Mp(I)=Force(I)*COS(Lamda(I)-Theta(I))*COS(Beta(I))*Height(I)
5000         M(I)=Height(I)*Ft(I)
5010         T(I)=Rho(I)*Ft(I)
5020      NEXT I
5030      RETURN
5040  !
5050 Data_shuffle:     !
5060      DISP "I'M DOING THE DATA SHUFFLE"
5070      Numb_terms=6
5080      IF Dead_count=0 THEN Dead_signal(1)=Numb_terms+1
5090      IF Dead_count=0 THEN Dead_signal(2)=Numb_terms+2
5100      IF Dead_count=1 THEN Dead_signal(2)=Numb_terms+1
```

```
5110      Numb_terms=Numb_terms-Dead_count
5120      J=0
5130      REDIM Z(400,Numb_terms)
5140      REDIM X(400,Numb_terms)
5150      FOR I=1 TO Numb_points
5160         FOR K=1 TO Dead_signal(1)-1
5170            Z(I,K)=Q(I,K)
5180         NEXT K
5190         FOR K=Dead_signal(1) TO Dead_signal(2)-2
5200            Z(I,K)=Q(I,K+1)
5210         NEXT K
5220         FOR K=Dead_signal(2)-1 TO Numb_terms
5230            Z(I,K)=Q(I,K+2)
5240         NEXT K
5250         IF Usage(I)=0 THEN Next_one
5260         J=J+1
5270         FOR K=1 TO Numb_terms
5280            X(J,K)=Z(I,K)
5290         NEXT K
5300         Mpx(J)=Mp(I)
5310         Ftx(J)=Ft(I)
5320         Mx(J)=M(I)
5330         Tx(J)=T(I)
5340 Next_one:        !
5350      NEXT I
5360      Numb_used_point=J
5370      RETURN
5380  !
5390 Print_a_matrix:   !
5400  !
5410      IMAGE SD.DDDE,4X,SD.DDDE,4X,SD.DDDE,4X,SD.DDDE,4X,SD.DDDE,4X,SD.DDDE
5420      A$=""
5430      PRINT
5440      PRINT TAB(20);"TABLE OF THE 'A' MATRIX";TAB(65);"VERSION NO: ";Version_
no$
5450      PRINT
5460      FOR I=1 TO 4
5470         PRINT USING 5410;A_matrix(I,1),A_matrix(I,2),A_matrix(I,3),A_matrix(
I,4),A_matrix(I,5),A_matrix(I,6)
5480      NEXT I
5490      IF A$="Y" THEN
5500         PRINT CHR$(12)
5510         GOTO 5580
5520      END IF
5530      INPUT "WOULD YOU LIKE HARDCOPY?",A$
5540      IF A$="Y" THEN
5550         PRINTER IS 701
5560         GOTO 5430
5570      END IF
5580      PRINTER IS 1
5590      RETURN
5600  !
5610 Regression:     !
5620  !
5630      MAT R= (0)
5640      REDIM R(Numb_terms)
5650      FOR I=1 TO Numb_used_point
5660         FOR J=1 TO Numb_terms
5670            R(J)=R(J)+X(I,J)*Y(I)
5680         NEXT J
5690      NEXT I
5700      REDIM A(Numb_terms)
5710      MAT A= Array_inv*R
5720      MAT Y_fit= Z*A
5730      RETURN
5740  !
```

```
5750 Invert_array:     !
5760  !
5770     DISP "INVERTING DATA MATRIX"
5780     Total=0
5790     MAT Array= (0)
5800     REDIM Array(Numb_terms,Numb_terms)
5810     REDIM Array_inv(Numb_terms,Numb_terms)
5820     FOR I=1 TO Numb_used_point
5830        FOR J=1 TO Numb_terms
5840           FOR K=1 TO J
5850              Array(J,K)=Array(J,K)+X(I,J)*X(I,K)
5860           NEXT K
5870        NEXT J
5880     NEXT I
5890     FOR J=1 TO Numb_terms
5900        FOR K=1 TO J
5910           Array(K,J)=Array(J,K)
5920        NEXT K
5930     NEXT J
5940     MAT Array_inv= INV(Array)
5950     IF DET=0 THEN Singular
5960     FOR J=1 TO Numb_terms
5970        FOR K=1 TO Numb_terms
5980           Total=Total+Array_inv(J,K)^2
5990        NEXT K
6000     NEXT J
6010     Test=DET/SQR(Total)
6020     IF Test<.001 THEN Ill_cond
6030     RETURN
6040  !
6050 Singular:        !
6060     DISP "SINGULAR MATRIX INVERSION  -  ERROR!"
6070     GOTO The_end
6080 Ill_con:         !
6090     DISP "ILL CONDITIONED MATRIX INVERSION  -  ERROR!"
6100 The_end:   !
6110     END
```

```
10    !    DATA INPUT PROGRAM FOR BLADE
20    !
30    !    WRITTEN BY: DOUG MONTGOMERY
40    !    DATE: MAY 8, 1984
50    !    VERSION: 1.00
60    !
70    !    MODIFIED BY:
80    !    DATE:
90    !    VERSION:
100   !    REASON:
110   !
120   OPTION BASE 1
130   !
140   REAL R_radius(40)                 ! RELATIVE RADIUS
150   REAL R_chord(40)                  ! RELATIVE CHORD
160   REAL Force(40)                    ! FORCE IN KILO-NEWTONS
170   REAL Force_mv(40)                 ! FORCE IN MILLI-VOLTS
180   REAL Theta(40)                    ! HORIZONTAL ANGLE IN DEGREES
190   REAL Beta(40)                     ! VERTICAL ANGLE IN DEGREES
200   REAL G(40,6)                      ! STRAIN GUAGE READINGS
210   DIM Comment$[80]                  ! COMMENT
220   REAL Slope                        ! FORCE CONVERSION SLOPE
230   REAL Offset                       ! FORCE CONVERSION OFFSET
240   !
250   Slope=.012
260   Offset=25
270   !
280   MASS STORAGE IS ":INTERNAL,4,0"
290   PRINTER IS 1
300   GCLEAR
310   PRINT CHR$(12)
320   GOSUB Get_case_no
330   IF Case_no$="" THEN STOP
340   GOSUB Read_data
350   DISP " "
360   GOSUB Print_data
370   ON KEY 0 LABEL "ADD DATA" GOSUB Get_data_points
380   ON KEY 1 LABEL "DELETE DATA" GOSUB Delete_points
390   ON KEY 2 LABEL "CHANGE DATA" GOSUB Change_points
400   ON KEY 3 LABEL "DISPLAY DATA" GOSUB Print_data
410   ON KEY 4 LABEL "EXIT" GOSUB Exit_data
420   ON KEY 5 LABEL "HARDCOPY" GOSUB Hardcopy
430   ON KEY 6 LABEL "SAVE DATA" GOSUB Save_data
440   ON KEY 7 LABEL " " GOTO Ignore
450   ON KEY 8 LABEL "HELP" GOSUB No_help
460   ON KEY 9 LABEL "FORCE CALIBRATE" GOSUB Force_calibrate
470   Exit_data=0
480 Ignore:     !
490      DISP "PRESS A KEY, ANY KEY, EVERYONES A WINNER"
500      IF NOT Exit_data THEN Ignore
510   GOSUB Print_data
520   GOSUB Save_data
530   STOP
540   !
550 Exit_data:   Exit_data=1
560   RETURN
570   !
580 No_help:     !
590   ALPHA OFF
600   GINIT
610   GRAPHICS ON
620   CSIZE 10
630   LORG 5
640   MOVE 50,50
650   LABEL "NO HELP HERE"
```

```
660   WAIT 1
670   GCLEAR
680   ALPHA ON
690   RETURN
700   !
710 Get_case_no:   !
720   Case_no$=""
730   INPUT "ENTER CASE NUMBER (1-10)",Case_no$
740   IF Case_no$="" THEN RETURN
750   ON ERROR GOTO Alpha_case
760   Case_no=VAL(Case_no$)
770   OFF ERROR
780   IF Case_no<1 OR Case_no>10 THEN DISP "CASE NUMBER MUST BE 1-10!  "
790   IF Case_no<1 OR Case_no>10 THEN Get_case_no
800   RETURN
810   !
820 Alpha_case:     !
830   DISP "CASE NUMBER MUST BE NUMERIC!  ";
840   OFF ERROR
850   GOTO Get_case_no
860   !
870 Hardcopy:       !
880   PRINTER IS 701
890   GOSUB Print_data
900   PRINT CHR$(12)
910   PRINTER IS 1
920   RETURN
930   !
940 Print_data:     !
950   !
960   PRINT TAB(20),"TEST CASE ",Case_no
970   PRINT Comment$
980   PRINT "SLOPE: ";Slope;TAB(20);"OFFSET: ";Offset
990   PRINT "I  RADIUS  CHORD  FORCE  THETA   BETA     G1     G2     G3     G4
   G5     G6"
1000  IMAGE  DD,2X,D.DDD,2X,D.DDD,3X,DD.D,X,MDDD.D,X,MDDD.D,2X,MDDDD,2X,MDDDD,2X
,MDDDD,2X,MDDDD,2X,MDDDD,2X,MDDDD
1010  PRINT " "
1020  FOR I=1 TO Number_of_data
1030      PRINT USING 1000;I,R_radius(I),R_chord(I),Force_mv(I)*Slope+Offset,Thet
a(I),Beta(I),G(I,1),G(I,2),G(I,3),G(I,4),G(I,5),G(I,6)
1040  NEXT I
1050  RETURN
1060  !
1070 Change_points:      !
1080  GOSUB Print_data
1090  ON ERROR GOTO Change_error
1100  Line_no$=""
1110  INPUT "ENTER LINE NUMBER TO BE CHANGED",Line_no$
1120  IF Line_no$="" THEN No_change
1130  Line_no=VAL(Line_no$)
1140  IF (Line_no<1) OR (Line_no>40) THEN Change_error
1150  IF Line_no>Number_of_data THEN No_change
1160  I=Line_no
1170  GOSUB Get_this_line
1180 No_change:     !
1190  OFF ERROR
1200  GOSUB Print_data
1210  RETURN
1220  !
1230 Change_error:     !
1240  DISP "LINE NUMBER ENTERED IN ERROR!  ";
1250  GOTO Change_points
1260  !
1270 Get_data_points:     !
1280  GOSUB Print_data
```

```
1290  FOR I=Number_of_data+1 TO 40
1300      GOSUB Get_this_line
1310      IF Data$="" THEN No_more
1320  NEXT I
1330 No_more:     !
1340  Number_of_data=I-1
1350  GOSUB Print_data
1360  RETURN
1370  !
1380 Get_this_line:     !
1390      ON ERROR GOTO Number_error
1400 Error_return:     !
1410      BEEP
1420      Data$=""
1430      INPUT "ENTER RELATIVE RADIUS ",Data$
1440      IF Data$="" THEN Thats_all
1450      R_radius(I)=VAL(Data$)
1460      PRINT TAB(1);I;
1470      PRINT TAB(9-LEN(VAL$(R_radius(I))));R_radius(I);
1480      INPUT "ENTER RELATIVE CHORD",Data$
1490      R_chord(I)=VAL(Data$)
1500      PRINT TAB(16-LEN(VAL$(R_chord(I))));R_chord(I);
1510      INPUT "ENTER FORCE (millivolts)",Data$
1520      Force_mv(I)=VAL(Data$)
1530      GOSUB Force_calculate
1540      PRINT TAB(23-LEN(VAL$(Force(I))));Force(I);
1550      INPUT "ENTER THETA (deg)",Data$
1560      Theta(I)=VAL(Data$)
1570      PRINT TAB(30-LEN(VAL$(Theta(I)))+(Theta(I)<0));Theta(I);
1580      INPUT "ENTER BETA (deg)",Data$
1590      Beta(I)=VAL(Data$)
1600      PRINT TAB(37-LEN(VAL$(Beta(I)))+(Beta(I)<0));Beta(I);
1610      FOR J=1 TO 6
1620         DISP "ENTER G";J;" ,( millivolts)";
1630         INPUT "",Value$
1640         G(I,J)=VAL(Value$)
1650         PRINT TAB(37+7*J-LEN(VAL$(G(I,J)))+(G(I,J)<0));G(I,J);
1660      NEXT J
1670 Thats_all:        !
1680      OFF ERROR
1690  RETURN
1700  !
1710 Number_error:     !
1720  DISP "NUMBER ENTERED IN ERROR, TRY AGAIN!  ";
1730  GOTO Error_return
1740  !
1750 Delete_points:  !
1760  GOSUB Print_data
1770  Line_no$=""
1780  ON ERROR GOTO Line_no_error
1790  INPUT "ENTER LINE TO BE DELETED (1-40)",Line_no$
1800  IF Line_no$="" THEN No_delete
1810  Line_no=VAL(Line_no$)
1820  IF Line_no>40 OR Line_no<1 THEN Line_no_error
1830  IF Line_no>Number_of_data THEN No_delete
1840  FOR I=Line_no TO Number_of_data-1
1850      R_radius(I)=R_radius(I+1)
1860      R_chord(I)=R_chord(I+1)
1870      Force_mv(I)=Force_mv(I+1)
1880      Force(I)=Force(I+1)
1890      Theta(I)=Theta(I+1)
1900      Beta(I)=Beta(I+1)
1910      FOR J=1 TO 6
1920         G(I,J)=G(I+1,J)
1930      NEXT J
1940  NEXT I
```

```
1950  R_radius(Number_of_data)=0
1960  R_chord(Number_of_data)=0
1970  Force_mv(Number_of_data)=0
1980  Force(Number_of_data)=0
1990  Theta(Number_of_data)=0
2000  Beta(Number_of_data)=0
2010  FOR J=1 TO 6
2020     G(Number_of_data,J)=0
2030  NEXT J
2040  Number_of_data=Number_of_data-1
2050 No_delete:     !
2060  OFF ERROR
2070  GOSUB Print_data
2080  RETURN
2090  !
2100 Line_no_error:     !
2110  DISP "LINE NUMBER ENTERED IN ERROR!  ";
2120  GOTO Delete_points
2130  !
2140 Read_data:     !
2150  !
2160  File_name$="BLADE_"&Case_no$
2170  Number_of_data=0
2180  ON ERROR GOTO Create_file
2190  ASSIGN @Path TO File_name$
2200  OFF ERROR
2210  DISP "READING BLADE DATA, PLEASE WAIT"
2220  ENTER @Path;Comment$
2230  ENTER @Path;Slope
2240  ENTER @Path;Offset
2250  ENTER @Path;R_radius(*)
2260  ENTER @Path;R_chord(*)
2270  ENTER @Path;Force_mv(*)
2280  ENTER @Path;Theta(*)
2290  ENTER @Path;Beta(*)
2300  ENTER @Path;G(*)
2310  ASSIGN @Path TO *
2320  FOR I=1 TO 40
2330      IF R_radius(I)=0 THEN No_more_data
2340  NEXT I
2350 No_more_data:   Number_of_data=I-1
2360  RETURN
2370  !
2380 Create_file:     !
2390  DISP "CREATING BLADE DATA FILE, PLEASE WAIT"
2400  ASSIGN @Path TO *
2410  CREATE BDAT File_name$,15
2420  OFF ERROR
2430  Comment$=""
2440  INPUT "ENTER COMMENT FOR NEW BLADE DATA FILE",Comment$
2450  GOSUB Force_calibrate
2460  RETURN
2470  !
2480 Save_data:  !
2490  File_name$="BLADE_"&Case_no$
2500  ASSIGN @Path TO File_name$
2510  DISP "SAVING BLADE DATA ONTO DISC"
2520  OUTPUT @Path;Comment$
2530  OUTPUT @Path;Slope
2540  OUTPUT @Path;Offset
2550  OUTPUT @Path;R_radius(*)
2560  OUTPUT @Path;R_chord(*)
2570  OUTPUT @Path;Force_mv(*)
2580  OUTPUT @Path;Theta(*)
2590  OUTPUT @Path;Beta(*)
2600  OUTPUT @Path;G(*)
```

```
2610  ASSIGN @Path TO *
2620  DISP "THAT'S ALL FOR NOW FOLKS"
2630  RETURN
2640  !
2650 Force_calibrate:   !
2660   Slope$=""
2670   DISP "SLOPE WAS ";Slope;
2680   INPUT " - INPUT SLOPE (OR PRESS CONT)",Slope$
2690   IF Slope$="" THEN Get_offset
2700   Slope=VAL(Slope$)
2710 Get_offset:     !
2720   Offset$=""
2730   DISP "OFFSET WAS ",Offset;
2740   INPUT " - INPUT OFFSET (OR PRESS CONT)",Offset$
2750   IF Offset$="" THEN RETURN
2760   Offset=VAL(Offset$)
2770   RETURN
2780   !
2790 Force_calculate:  !
2800    Force(I)=Offset+Slope*Force_mv(I)
2810    RETURN
2820  END
```

# APPENDIX E
# DATA ACQUISITION AND PLOTTING ROUTINE FOR WURMLINGER STATIC CALIBRATION TESTS

```
10   ! Program HSDAR /M. H. Edgecombe /84-05-17
20   !
30   ! VERSION HSDAR4_3 TO INCLUDE CALCULATION OF LEAST SQUARE FIT OF G1 TO G6
40   ! AND LEAST SQUARED FIT OF SELECTED POINTS
50   ! P.A.S. 84/05/24
60   !
70   ! MODIFIED BY : KEN KIRBY
80   ! DATE        : 84-10-22
90   ! REASON      : TO CALCULATE SLOPE OF SELECTED POINTS
100  !               CHANGE FORMAT OF GRAPH
110  !               GOT RID OF NEGATIVE SIGN ON LOAD CELL VOLTAGE
120  !
130  ! MODIFIED BY : KEN KIRBY
140  ! DATE        : 84-11-09
150  ! REASON      : TO ALLOW DATA TO BE SCALED AS IF IT HAD BEEN RECORDED
160  !               AT THE SAME GAINS AS DURING THE SHIP TESTING PERIOD
170  !               WITH A MESSAGE AS TO THE SCALE USED
180  !
190  ! MODIFIED BY :
200  ! DATE        :
210  ! REASON      :
220  !
230  ! High Speed Data Acquisition Routine for the HP 9836 desktop computer
240  ! and the HP 6940B multiprogrammer.
250  !
260  ! Hardware Configuration:
270  !     - 1 of HP Series 200 model 36 desktop computer (HP 9836)
280  !     - 6 of HP 98256 256K RAM memory boards installed in the 9836
290  !     - 1 of HP 98622A opt. 003 GP-IO interface (select code 12)
300  !
310  !     - 1 of HP 6940B multiprogrammer mainframes connected to the HP9836
320  !       via the HP 98622A GP-IO interface and opt. 003 cable.
330  !     - 1 of HP 69331B voltage regulator card installed in m/p slot 600
340  !     - 1 of HP 69602A timer/pacer card installed in m/p slot 400
350  !     - 1 of HP 69422A high speed a/d card installed in m/p slot 401
360  !     - 2 of HP 69336B high speed scanner cards installed in m/p slots 402
370  !       and 403
380  !
390  ! Operating System and Extensions:
400  !     - BASIC 2.0
410  !     - BASIC Extensions 2.1
420  !
430    OPTION BASE 1
440    INTEGER I,J,K,L,M,N,Nchnls,Nrdgs,Nbytes,Range
450    INTEGER Period,Nscans,Form,Lines,Start_line
460    INTEGER V(1,8) BUFFER,A(1,8),Rdgs(500,8)
470    DIM Title$[80],Date$[12],Time$[12],Sig$(2,8)[9],File$[25],Slope(7),Interc
ept(7),Value(7),Message_scale$[80],Comp_tests$(50)[10]
480    REAL Sumx,Sumxsq,Sumy,Sumxy,Xpoint,Ypoint
490   !
500    Scan_period=.1
510    Nchnls=8
520    Nrdgs=1
530    Nwords=Nrdgs*Nchnls
540    Nbytes=Nwords*2
550    Form=18
560    Phi=9999
570    !
580    DATA "    LE   ","    LE   ","    TE   ","    TE   "
590    DATA "  CENTRE ","  CENTRE "," SLIDING "," APPLIED "
600    DATA " BENDING ","  TORQUE "," BENDING ","  TORQUE "
610    DATA " BENDING ","  TORQUE ","  BLOCK  ","   LOAD  "
620    READ Sig$(*)
630    !
640    DATA "PT1_C2    ","PT1_C3    ","PT2_C1    ","PT2_C1_2  ","PT2_C2    "
650    DATA "PT2_C3    ","PT4_C2    ","PT4_C3    ","PT4_C5    ","PT5_C3    "
```

```
660    DATA "PT5_C5     ","PT7_C2     ","PT7_C3     ","PT7_C4     ","PT8_C3     "
670    DATA "PT9_C2     ","PT9_C3     ","PT9_C3_2   ","PT10_C2    ","PT10_C3    "
680    DATA "PT10_C4    ","PT11_C2    ","PT11_C4    ","PT12_C2    ","PT12_C2_2  "
690    DATA "PT12_C3    ","PT15_C2    ","PT15_C3    ","PT17_C2    ","PT17_C3    "
700    DATA "PT19_C3    ","PT20_C3    ","PT21_C2    ","PT22_C2    ","PT22_C3    "
710    DATA "PT24_C2    ","PT24_C3    ","PT24_C4    ","PT24_C5    ","PT25_C2    "
720    DATA "PT25_C3    ","PT29_C2    ","PT29_C3    ","PT30_C2    ","PT31_C2    "
730    DATA "PT32_C2    ","PT32_C3    ","PT33_C3    ","PT34_C2    ","PT35_C2    "
740    READ Comp_tests$(*)
750    !
760    All_tests=50
770    !
780    ASSIGN @Buffer TO BUFFER V(*);WORD
790 !ASSIGN @Multiprogrammer TO 12;WORD
800   !
810    Timer_card=0
820    Ad_card=4096
830    Scanner_card0=8192
840    Scanner_card1=12288
850    Cw=-4096
860    Isl=128
870    Dte=64
880    Sye=32
890    Tme=16
900    Point_plot=1
910 Ctl_fmt:IMAGE #,W
920   !
930   ! ****************************************************************
940   ! START
950   ! ****************************************************************
960 Start:  !
970    ON ERROR GOTO Driver
980    IF TIMEDATE<2.09E+11 THEN GOSUB Set_time
990    Nscans=0
1000   Change_gain=1
1010   GOTO Scale_data
1020  !
1030  ! **************************************************************
1040  ! DRIVER
1050  ! **************************************************************
1060 Driver: !
1070   Other_idle=0
1080   OFF KEY
1090   ON KEY 0 LABEL "START SCAN",3 GOTO Scan
1100   ON KEY 5 LABEL "STOP SCAN",3 GOTO Driver
1110   ON KEY 1 LABEL "LIST DATA",3 GOTO List_data
1120   ON KEY 6 LABEL "PLOT DATA",3 GOTO Graphics
1130   ON KEY 2 LABEL "SAVE DATA",3 GOTO Save_data
1140   ON KEY 7 LABEL "GET DATA",3 GOTO Get_data
1150   ON KEY 3 LABEL "SLOPES",3 GOTO Slopes
1160   ON KEY 4 LABEL "SCALE",3 GOTO Scale_data
1170   ON KEY 8 LABEL " ",3 GOTO Idle
1180   ON KEY 9 LABEL " ",3 GOTO Idle
1190 !
1200 Idle:!
1210   IF NOT Other_idle THEN
1220      GOSUB Display_time
1230      GOTO Idle
1240   ELSE
1250      GOTO G_idle
1260   END IF
1270 !
1280 ! ***************************************************************
1290 ! SCAN
1300 ! ***************************************************************
1310 Scan: !
```

```
1320   PRINT CHR$(12)
1330   GOSUB Print_header
1340 !
1350 ! ************************************************************************
1360 ! SAMPLE LOOP
1370 ! ************************************************************************
1380 Sample_loop:!
1390   GOSUB Sample
1400   I=Nscans
1410   GOSUB Print_volts
1420   IF Lines>=Form THEN GOSUB Print_header
1430   WAIT Scan_period
1440   GOTO Sample_loop
1450  !
1460 ! ***********************************************************************
1470 ! SAMPLE
1480 ! ***********************************************************************
1490 Sample:  !
1500   DISABLE
1510   RESET 12
1520   Range=0          ! timer increment is 10^Range microseconds
1530   Range=2^Range
1540   Period=500       ! time between channels is 2XPeriod*Range
1550   Start_channel=7
1560 !
1570 ! ***********************************************************************
1580 ! SAMPLE RATE
1590 ! ***********************************************************************
1600 Sample_rate: !
1610   OUTPUT 12 USING Ctl_fmt;Cw+Sye
1620   OUTPUT 12 USING Ctl_fmt;Timer_card+3072+Range
1630   OUTPUT 12 USING Ctl_fmt;Timer_card+Period
1640 !
1650 ! ***********************************************************************
1660 ! START CHANNEL
1670 ! ***********************************************************************
1680 Start_chan: !
1690   OUTPUT 12 USING Ctl_fmt;Cw+Sye
1700   OUTPUT 12 USING Ctl_fmt;Scanner_card1+2048+16           ! 2048=disabled
1710   OUTPUT 12 USING Ctl_fmt;Scanner_card0+Start_channel     ! enabled
1720 !
1730 ! **********************************************************************
1740 ! ADDRESS A/D CARD
1750 ! **********************************************************************
1760 Address_adc: !
1770   OUTPUT 12 USING Ctl_fmt;Cw+Isl+Sye+Tme
1780   CONTROL 12,3;Ad_card
1790 !
1800 ! *********************************************************************
1810 ! TRANSFER DATA
1820 ! *********************************************************************
1830 Transfer: !
1840   T1=TIMEDATE
1850   TRANSFER @Multiprogrammer TO @Buffer;COUNT Nbytes,WAIT
1860 ! Busy:   STATUS @Buffer,10;Stat
1870 !          IF BIT(Stat,6) THEN Busy
1880   T2=TIMEDATE
1890 !
1900 ! **********************************************************************
1910 ! SHUT DOWN DATA TRANSFER
1920 ! **********************************************************************
1930 Shut_down: !
1940   OUTPUT 12 USING Ctl_fmt;Cu+Sye+Dte
1950   OUTPUT 12 USING Ctl_fmt;Timer_card+Period
1960   OUTPUT 12 USING Ctl_fmt;Timer_card+3072
1970 !
```

```
1980 !
1990 ! *********************************************************************
2000 ! CONVERT READINGS TO BIT COUNTS
2010 ! *********************************************************************
2020 Convert: !
2030   MAT V= V+(32768)
2040   MAT A= (2047)
2050   MAT A= V>A
2060   MAT A= A*(-4096)
2070   MAT V= V+A
2080   !
2090   Nscans=Nscans+1
2100   FOR I=1 TO 8
2110      Rdgs(Nscans,I)=V(1,I)
2120   NEXT I
2130   !
2140   CONTROL @Buffer,5;1
2150   CONTROL @Buffer,4;1
2160   CONTROL @Buffer,3;1
2170   IF Nscans>=500 THEN GOTO Driver
2180   !
2190   ENABLE
2200   RETURN
2210 !
2220 ! ***********************************************************************
2230 ! GRAPHICS
2240 ! ***********************************************************************
2250 Graphics: !
2260   Other_idle=1
2270   GCLEAR
2280   Join$=""
2290   INPUT "ENTER NUMBER OF SIGNAL TO BE PLOTTED...",Sig
2300   Xmin=-7
2310   Ymin=-.20
2320   Xmax=1
2330   Ymax=.8
2340   PRINT CHR$(12)
2350   GOSUB Plot
2360   !
2370   ON KNOB .1,9 GOSUB Move_cursor
2380   !
2390   ON KEY 0 LABEL "Increase YMAX",3 GOTO Ymaxinc
2400   ON KEY 1 LABEL "Decrease YMAX",3 GOTO Ymaxdec
2410   ON KEY 5 LABEL "Decrease YMIN",3 GOTO Ymindec
2420   ON KEY 6 LABEL "Increase YMIN",3 GOTO Ymininc
2430   ON KEY 4 LABEL "New Plot",3 GOTO Graphics
2440   ON KEY 2 LABEL "Least Square",3 GOTO Mod_least_sq
2450   ON KEY 7 LABEL "Lower Limit",3 GOTO Lower_limit
2460   ON KEY 8 LABEL "Upper Limit",3 GOTO Upper_limit
2470   ON KEY 9 LABEL "EXIT",3 GOTO Exit
2480   ON KEY 3 LABEL "POINTS/LINE",3 GOTO Points_line
2490   OFF ERROR
2500 G_idle:GOTO G_idle
2510  !
2520  ! *********************************************************************
2530  ! Y MAXIMUM INCREASE
2540  ! *********************************************************************
2550 Ymaxinc:Ymax=Ymax+.1
2560   GOSUB Plot
2570   GOTO G_idle
2580  !
2590  ! *********************************************************************
2600  ! Y MAXIMUM DECREASE
2610  ! *********************************************************************
2620 Ymaxdec:IF Ymax>=Ymin+.2 THEN Ymax=Ymax-.1
2630   GOSUB Plot
```

```
2640  GOTO G_idle
2650  !
2660  ! *************************************************************************
2670  ! Y MINIMUM DECREASE
2680  ! *************************************************************************
2690 Ymindec:Ymin=Ymin-.1
2700  GOSUB Plot
2710  GOTO G_idle
2720  !
2730  ! *************************************************************************
2740  ! Y MINIMUM INCREASE
2750  ! *************************************************************************
2760 Ymininc:IF Ymax>=Ymin+.2 THEN Ymin=Ymin+.1
2770  GOSUB Plot
2780  GOTO G_idle
2790  !
2800  ! ************************************************************************
2810  ! POINTS LINE
2820  ! ************************************************************************
2830 Points_line: !DETERMINES IF POINTS ARE TO BE PLOTTED OR JOINED WITH LINES
2840  IF Point_plot=1 THEN
2850     Point_plot=0
2860  ELSE
2870     Point_plot=1
2880  END IF
2890  BEEP
2900  RETURN
2910  !
2920  ! ************************************************************************
2930  ! PLOT
2940  ! ************************************************************************
2950 Plot:  !
2960  GCLEAR
2970  DEG
2980  GINIT
2990  CLIP ON
3000  VIEWPORT 15,130,13,90
3010  GRAPHICS ON
3020  FRAME
3030  WINDOW Xmin,Xmax,Ymin,Ymax
3040  IF Ymax-Ymin>=.50 THEN
3050     AXES .2,.1,Xmin,Ymin,5,5,2
3060  ELSE
3070     AXES .2,.02,Xmin,Ymin,5,5,2
3080  END IF
3090  !
3100  MOVE Xmin,0                                 ! DRAWS LINES AT (0,0)
3110  PLOT Xmax,0,-1
3120  MOVE 0,Ymin
3130  PLOT 0,Ymax,-1
3140  !
3150  LDIR 0                                      ! LABLES X-AXIS
3160  LORG 6
3170  CSIZE 2.5
3180  CLIP OFF
3190  FOR X=Xmin TO Xmax
3200     IF ABS(X)<1.E-6 THEN X=0
3210     MOVE X,-.01*(Ymax-Ymin)+Ymin
3220     LABEL USING "K";X
3230 Next_x:NEXT X
3240  !
3250  CSIZE 3.5
3260  MOVE .5*(Xmax+Xmin),-.05*(Ymax-Ymin)+Ymin
3270  LABEL USING "K";"LOAD CELL OUTPUT (volts)"
3280  !
3290  CSIZE 2.5                                       ! LABLES Y-AXIS
```

```
3300   LORG 8
3310   !
3320   IF Ymax-Ymin>=2 THEN
3330      FOR Y=Ymin TO Ymax
3340         IF ABS(Y)<1.E-6 THEN Y=0
3350         MOVE -.015*(Xmax-Xmin)+Xmin,Y
3360         LABEL USING "K";Y
3370      NEXT Y
3380   ELSE
3390      IF Ymax-Ymin>=.50 THEN
3400         FOR Y=Ymin TO Ymax STEP .1
3410            IF ABS(Y)<1.E-6 THEN Y=0
3420            MOVE -.015*(Xmax-Xmin)+Xmin,Y
3430            LABEL USING "K";Y
3440 Next_y_1:NEXT Y
3450      ELSE
3460         FOR Y=Ymin TO Ymax STEP .02
3470            IF ABS(Y)<1.E-6 THEN Y=0
3480            MOVE -.015*(Xmax-Xmin)+Xmin,Y
3490            LABEL USING "K";Y
3500 Next_y_2:NEXT Y
3510      END IF
3520   END IF
3530  !
3540   LDIR 90
3550   LORG 4
3560   CSIZE 3.5
3570   MOVE -.07*(Xmax-Xmin)+Xmin,.5*(Ymax+Ymin)
3580   LABEL USING "K";Sig$(1,Sig)&Sig$(2,Sig)&" (volts)"
3590  !
3600   LDIR 0                                              ! TITLES GRAPH
3610   LORG 6
3620   MOVE .5*(Xmax+Xmin),Ymax+.10*(Ymax-Ymin)
3630   LABEL USING "K";Title$
3640  !
3650   MOVE .5*(Xmax+Xmin),Ymax+.05*(Ymax-Ymin)            ! TELLS GAINS USED
3660   LABEL USING "K";Message_scale$
3670  !
3680   IF Sig>7 THEN RETURN
3690   LORG 5                                              ! PLOTS POINTS
3700   MOVE Rdgs(1,8)*.005,Rdgs(1,Sig)*.005
3710   CSIZE 2.0
3720   IF Point_plot THEN LABEL USING "K";"+"
3730   FOR I=2 TO Nscans
3740      IF Point_plot THEN
3750         MOVE Rdgs(I,8)*.005,Rdgs(I,Sig)*.005
3760         LABEL USING "K";"+"
3770      ELSE
3780         PLOT Rdgs(I,8)*.005,Rdgs(I,Sig)*.005,-1
3790      END IF
3800   NEXT I
3810  !
3820   CLIP ON
3830   MOVE Xmin,(Intercept(Sig)+Xmin/.005*Slope(Sig))*.005
3840   PLOT Xmax,(Intercept(Sig)+Xmax/.005*Slope(Sig))*.005,-1
3850   CLIP OFF
3860   DISP " SLOPE = ",Slope(Sig)
3870  !
3880   RETURN
3890  !
3900  ! *******************************************************************
3910  ! EXIT .
3920  ! *******************************************************************
3930 Exit:GCLEAR
3940   GOTO Driver
3950  !
```

```
3960  ! ******************************************************************
3970  ! LIST DATA
3980  ! ******************************************************************
3990 List_data:  !
4000   OFF KEY
4010   ON KEY 5 LABEL "CONT",3 GOTO List_start
4020   ON KEY 9 LABEL "EXIT",3 GOTO Driver
4030   ON KEY 1 LABEL " ",3 GOTO Idle
4040   ON KEY 2 LABEL " ",3 GOTO Idle
4050   ON KEY 3 LABEL " ",3 GOTO Idle
4060   ON KEY 4 LABEL " ",3 GOTO Idle
4070   ON KEY 6 LABEL " ",3 GOTO Idle
4080   ON KEY 7 LABEL " ",3 GOTO Idle
4090   ON KEY 8 LABEL " ",3 GOTO Idle
4100   Start_line=1
4110   !
4120  ! ******************************************************************
4130  ! LIST START
4140  ! ******************************************************************
4150 List_start:   !
4160   PRINT CHR$(12)
4170   IF Message_scale$<>"" THEN
4180      PRINT Message_scale$
4190      PRINT
4200   END IF
4210   !
4220   IF Title$<>"" THEN PRINT Title$;"  Phi =";Phi;"  Theta =";Theta;"    ";Ti
me$;"  ";Date$
4230   GOSUB Print_header
4240   Lines=5
4250  !
4260   FOR I=Start_line TO Nscans
4270      GOSUB Print_volts
4280      IF Lines>=Form THEN New_page
4290   NEXT I
4300  !
4310  ! ******************************************************************
4320  ! NEW PAGE
4330  ! ******************************************************************
4340 New_page:IF I<Nscans THEN Start_line=I+1
4350   GOTO Idle
4360  !
4370  ! ******************************************************************
4380  ! PRINT HEADER
4390  ! ******************************************************************
4400 Print_header:  !
4410   PRINT
4420   PRINT "        ";
4430   FOR I=1 TO 8
4440      PRINT Sig$(1,I);
4450   NEXT I
4460   PRINT
4470   PRINT "        ";
4480   FOR I=1 TO 8
4490      PRINT Sig$(2,I);
4500   NEXT I
4510   PRINT USING "/"
4520   Lines=5
4530   RETURN
4540  !
4550  ! ******************************************************************
4560  ! PRINT VOLTS
4570  ! ******************************************************************
4580 Print_volts:  !
4590   PRINT USING "2X,DDD,2X,#";I
4600   FOR J=1 TO 8
```

```
4610         PRINT USING "X,MDD.DDD,1X,#";Rdgs(I,J)*.005
4620      NEXT J
4630      PRINT
4640      Lines=Lines+1
4650      RETURN
4660     !
4670     ! ***********************************************************************
4680     ! SAVE DATA
4690     ! ***********************************************************************
4700 Save_data:   !
4710      Time$=FNTime$(TIMEDATE)
4720      Date$=FNDate$(TIMEDATE)
4730      DISP Time$,Date$;
4740      INPUT "  ENTER TEST TITLE (80 char. max.)...",Title$
4750      INPUT "ENTER LOADING ANGLE RELATIVE TO RADIAL DIRECTION...",Phi
4760      INPUT "ENTER LOADING ANGLE RELATIVE TO CIRCUMFERENTIAL DIRECTION...",Thet
a
4770      INPUT "ENTER NAME OF OUTPUT DATA FILE...",File$
4780      Rec=(80+40+10+10+2+500*8*2)/256
4790      CREATE BDAT File$,Rec
4800      ASSIGN @Outfile TO File$
4810      OUTPUT @Outfile;Title$,Date$,Time$,Phi,Theta,Nscans,Rdgs(*)
4820      ASSIGN @Outfile TO *
4830      GOTO Driver
4840     !
4850     ! ***********************************************************************
4860     ! GET DATA
4870     ! ***********************************************************************
4880 Get_data:   !
4890      Disk_read=0
4900      MASS STORAGE IS ":INTERNAL,4,0"
4910      ON ERROR GOSUB Other_disk
4920      IF All_cases THEN
4930         File$=Comp_tests$(Numb)
4940      ELSE
4950         INPUT "ENTER NAME OF DATA FILE TO BE READ...",File$
4960      END IF
4970      ASSIGN @Infile TO File$
4980      OFF ERROR
4990      ENTER @Infile;Title$,Date$,Time$,Phi,Theta,Nscans,Rdgs(*)
5000      ASSIGN @Infile TO *
5010      MASS STORAGE IS ":INTERNAL,4,0"
5020      !
5030      IF Change_gain THEN
5040         FOR I=1 TO Nscans
5050            FOR J=1 TO 6
5060               Rdgs(I,J)=INT(Rdgs(I,J)/5+.5)
5070            NEXT J
5080         NEXT I
5090      END IF
5100      !
5110      GOSUB Least_square
5120      DISP ""
5130      IF Slope_table THEN RETURN
5140      GOTO Graphics
5150     !
5160     ! ***********************************************************************
5170     ! SCALE DATA
5180     ! ***********************************************************************
5190 Scale_data:  ! CAN TREAT DATA TO AS IF IT HAD BEEN RECORDED AT LOWER GAIN
5200      IF Change_gain=0 THEN
5210         Change_gain=1
5220         Message_scale$=" AMPLIFIER GAINS USED ARE: CH1-6 400; CH7 1000; CH8 50
0 "
5230         DISP " DATA IS TREATED AS IF AMPLIFIER GAINS ARE THOSE USED DURING SHI
P TESTS"
```

```
5240   ELSE
5250      Change_gain=0
5260      Message_scale$=" AMPLIFIER GAINS USED ARE: CH1-6 2000; CH7 1000; CH8 5
00"
5270      DISP " DATA IS PRESENTED USING ACTUAL GAINS DURING CALIBRATION TESTS"
5280   END IF
5290   BEEP
5300   WAIT 2
5310   GOTO Driver
5320   ! ****************************************************************
5330   ! OTHER DISK
5340   ! ****************************************************************
5350 Other_disk:  ! CHECKS IF THE DISK INSERTED IS NOT THE CORRECT ONE
5360   IF ERRN=56 AND Disk_read=0 THEN
5370      MASS STORAGE IS ":INTERNAL,4,1"
5380      Disk_read=1
5390   ELSE
5400   !
5410      IF ERRN=56 AND Disk_read=1 THEN
5420         INPUT "ENTER NAME OF DATA FILE TO BE READ...AGAIN>>>",File$
5430         BEEP
5440         Disk_read=0
5450         MASS STORAGE IS ":INTERNAL,4,0"
5460      END IF
5470   !
5480      IF ERRN<>56 THEN
5490         MASS STORAGE IS ":INTERNAL,4,0"
5500         DISP "UNEXPECTED ERROR ",ERRN,"HAS OCCURED"
5510         MASS STORAGE IS ":INTERNAL,4,0"
5520         BEEP
5530         PAUSE
5540      END IF
5550   END IF
5560   RETURN
5570   !
5580   ! ****************************************************************
5590   ! SET TIME
5600   ! ****************************************************************
5610 Set_time:  !
5620   INPUT "ENTER CURRENT DATE (DD MMM YYYY)...",Date$
5630   SET TIMEDATE FNDate(Date$)
5640   INPUT "ENTER CURRENT TIME (HH:MM:SS)...",Time$
5650   SET TIME FNTime(Time$)
5660   RETURN
5670   !
5680   ! ****************************************************************
5690   ! DISPLAY TIME
5700   ! ****************************************************************
5710 Display_time:  !
5720   DISP FNTime$(TIMEDATE),FNDate$(TIMEDATE)
5730   RETURN
5740   !
5750   ! ****************************************************************
5760   ! LEAST SQUARE FIT
5770   ! ****************************************************************
5780 Least_square:  !
5790   DISP "CALCULATING BEST FIT LINES"
5800   Conversion=1
5810   FOR J=1 TO 7
5820      Sumx=0
5830      Sumy=0
5840      Sumxy=0
5850      Sumxsq=0
5860      FOR I=1 TO Nscans
5870         Xpoint=Rdgs(I,8)
5880         Ypoint=Rdgs(I,J)
```

```
5890         Sumx=Sumx+Xpoint
5900         Sumxsq=Sumxsq+Xpoint*Xpoint
5910         Sumy=Sumy+Ypoint
5920         Sumxy=Sumxy+Xpoint*Ypoint
5930      NEXT I
5940      Delta=Nscans*Sumxsq-Sumx*Sumx
5950      Slope(J)=Conversion*(Nscans*Sumxy-Sumx*Sumy)/Delta
5960      Intercept(J)=(Sumy*Sumxsq-Sumx*Sumxy)/Delta
5970      Value(J)=Slope(J)*10/(-1.366*.005)      ! mV OUTPUT/10kN LOAD USING
                                                    MEASURED CALIBRATION
5980  !   Value(J)=Slope(J)*1000/-7.22           ! mV. OUTPUT/kN LOAD USING
                                                    MANUFACTURES CALIBRATION
5990   NEXT J
6000  !
6010   IF Slope_table THEN RETURN
6020   PRINT Message_scale$
6030   PRINT ""
6040   PRINT Title$
6050   PRINT "   LEAST SQUARES BEST FIT VALUES"
6060   PRINT "FILE       GAGE       SLOPE      MEASURED "
6070   PRINT "NAME       NUMBER     BITS/BIT  mV/10kN  "
6080   PRINT
6090   FOR J=1 TO 7
6100      IF ABS(Slope(J))>999 OR ABS(Value(J))>999 THEN
6110         PRINT USING "8A,2X,2D,8X,MD.2DE,X,MD.2DE";File$,J,Slope(J),Value(J)
6120      ELSE
6130         PRINT USING "8A,2X,2D,8X,M3D.3D,3X,M3D.3D";File$,J,Slope(J),Value(J
)
6140      END IF
6150   NEXT J
6160   RETURN
6170  !
6180  ! ************************************************************************
6190  ! MODIFIED LEAST SQUARE FIT
6200  ! ************************************************************************
6210 Mod_least_sq:  ! FINDS BEST LINE THROUGH CHOOSEN POINTS
6220   Conversion=1
6230   Sumx=0
6240   Sumy=0
6250   Sumxy=0
6260   Sumxsq=0
6270   First_1=First
6280   Last_1=Last
6290   First=MIN(First_1,Last_1)
6300   Last=MAX(First_1,Last_1)
6310   IF First=0 OR Last=0 OR Last=First THEN
6320      BEEP
6330      DISP " YOU MUST CHOOSE THE LIMITS AGAIN"
6340   ELSE
6350      FOR I=First TO Last
6360         Xpoint=Rdgs(I,8)
6370         Ypoint=Rdgs(I,Sig)
6380         Sumx=Sumx+Xpoint
6390         Sumxsq=Sumxsq+Xpoint*Xpoint
6400         Sumy=Sumy+Ypoint
6410         Sumxy=Sumxy+Xpoint*Ypoint
6420      NEXT I
6430      Delta=(Last-First+1)*Sumxsq-Sumx*Sumx
6440      Mod_slope=Conversion*((Last-First+1)*Sumxy-Sumx*Sumy)/Delta
6450      Mod_intercept=(Sumy*Sumxsq-Sumx*Sumxy)/Delta
6460      LINE TYPE 1
6470      PEN 1
6480      MOVE Rdgs(First,8)*.005,(Mod_intercept+Mod_slope*Rdgs(First,8))*.005
6490      DRAW Rdgs(Last,8)*.005,(Mod_intercept+Mod_slope*Rdgs(Last,8))*.005
6500      DISP "SLOPE= ",Mod_slope
6510      BEEP
```

```
6520   END IF
6530   RETURN
6540  !
6550  ! ****************************************************************
6560  ! SLOPES
6570  ! ****************************************************************
6580 Slopes:  ! GIVES TABLE OF BEST FIT LINES FOR ALL GAGES IN ALL CASES
6590   Slope_table=1
6600   PRINTER IS 1
6610   Inpt$=""
6620   INPUT " DO YOU WANT HARD COPY : Y or CONT",Inpt$
6630   IF UPC$(Inpt$)="Y" THEN PRINTER IS 701
6640   Inpt$=""
6650   All_cases=0
6660   Numb=1
6670   INPUT " DO YOU WANT THE SLOPES FOR ALL CASES? : Y or CONT",Inpt$
6680   IF UPC$(Inpt$)="Y" THEN All_cases=1
6690 Next_page:PRINT CHR$(12)
6700   Lines=0
6710   PRINT Message_scale$
6720   PRINT
6730   PRINT "                 GAGE OUTPUT VOLTAGE PER APPLIED LOAD ( mV/10kN ) "
6740   PRINT " TITLE       GAGE #1   GAGE #2   GAGE #3   GAGE #4   GAGE #5   GAGE
 #6   GAGE #7 "
6750 Next_slope:GOSUB Get_data
6760   IF MAX(Value(*))>999 OR MIN(Value(*))<-999 THEN
6770      PRINT USING Slope_eng;File$,Value(*)
6780 Slope_eng:IMAGE 10A,7(X,MD.2DE)
6790   ELSE
6800      PRINT USING Slope_output;File$,Value(*)
6810 Slope_output:IMAGE 10A,7(2X,M3D.3D)
6820   END IF
6830   !
6840   Lines=Lines+1
6850   IF NOT All_cases THEN
6860      Inpt$=""
6870      INPUT "DO YOU WANT ANOTHER FILE OUTPUT : N or CONT",Inpt$
6880      IF UPC$(Inpt$)="N" THEN Slopes_exit
6890      IF Lines<=50 THEN Next_slope
6900   ELSE
6910      Numb=Numb+1
6920      IF Numb>All_tests THEN Slopes_exit
6930      IF Lines<=50 THEN Next_slope
6940   END IF
6950   GOTO Next_page
6960  !
6970  ! ****************************************************************
6980  ! SLOPES_EXIT
6990  ! ****************************************************************
7000 Slopes_exit:  ! EXITS FROM SLOPES ROUTINE
7010   Slope_table=0
7020   PRINTER IS 1
7030   GOTO Driver
7040  !
7050  ! ****************************************************************
7060  ! MOVE CURSOR
7070  ! ****************************************************************
7080 Move_cursor:  !
7090   PEN 0
7100   LORG 5
7110   CSIZE 3.5
7120   IF Position=0 THEN Position=1
7130   MOVE Rdgs(Position,8)*.005,Rdgs(Position,Sig)*.005
7140   LABEL "O"
7150   Position=Position+INT(KNOBX)
7160   IF Position<=1 THEN Position=Nscans
```

```
7170   IF Position>Nscans THEN Position=1
7180   MOVE Rdgs(Position,8)*.005,Rdgs(Position,Sig)*.005
7190   LABEL "O"
7200   PEN 1
7210   Reading_sec=Position*.1
7220   DISP USING "DD.D";Reading_sec
7230   RETURN
7240   !
7250   ! ********************************************************************
7260   ! LOWER LIMIT
7270   ! ********************************************************************
7280 Lower_limit:   !
7290   BEEP
7300   First=Position
7310   RETURN
7320   !
7330   ! ********************************************************************
7340   ! UPPER LIMIT
7350   ! ********************************************************************
7360 Upper_limit:   !
7370   BEEP
7380   Last=Position
7390   RETURN
7400   !
7410   ! ********************************************************************
7420   ! THE END
7430   ! ********************************************************************
7440 The_end:   !
7450  !
7460   END
7470  !
7480  !
7490   DEF FNTime$(Now)
7500      Now=INT(Now) MOD 86400
7510      H=Now DIV 3600
7520      M=Now MOD 3600 DIV 60
7530      S=Now MOD 60
7540      OUTPUT T$ USING "#,ZZ,K";H,":",M,":",S
7550      RETURN T$
7560   FNEND
7570  !
7580   DEF FNTime(T$)
7590      ON ERROR GOTO Err
7600      ENTER T$;H,M,S
7610      RETURN (3600*H+60*M+S) MOD 86400
7620 Err: OFF ERROR
7630      RETURN TIMEDATE MOD 86400
7640   FNEND
7650   !
7660   DEF FNDate$(Seconds)
7670      DATA JAN,FEB,MAR,APR,MAY,JUN,JUL,AUG,SP,OCT,NOV,DEC
7680      DIM Month$(1:12)[3]
7690      READ Month$(*)
7700   !
7710      Julian=Seconds DIV 86400-1721119
7720      Year=(4*Julian-1) DIV 146097
7730      Julian=(4*Julian-1) MOD 146097
7740      Day=Julian DIV 4
7750      Julian=(4*Day+3) DIV 1461
7760      Day=(4*Day+3) MOD 1461
7770      Day=(Day+4) DIV 4
7780      Month=(5*Day-3) DIV 153
7790      Day=(5*Day-3) MOD 153
7800      Day=(Day+5) DIV 5
7810      Year=100*Year+Julian
7820      IF Month<10 THEN
```

```
7830          Month=Month+3
7840       ELSE
7850          Month=Month-9
7860          Year=Year+1
7870       END IF
7880       OUTPUT D$ USING "#,ZZ,X,3A,X,4Z";Day,Month$(Month),Year
7890       RETURN D$
7900    FNEND
7910   !
7920    DEF FNDate(Dmy$)
7930       DATA JAN,FEB,MAR,APR,MAY,JUN,JUL,AUG,SEP,OCT,NOV,DEC
7940       DIM Month$(1:12)[3]
7950       READ Month$(*)
7960   !
7970       ON ERROR GOTO Err
7980       I$=Dmy$&"     "
7990       ENTER I$ USING "DD,4A,5D,";Day,M$,Year
8000       IF Year<100 THEN Year=Year+1900
8010       FOR I=1 TO 12
8020          IF POS(M$,Month$(I)) THEN Month=I
8030       NEXT I
8040       IF Month=0 THEN Err
8050       IF Month>2 THEN
8060          Month=Month-3
8070       ELSE
8080          Month=Month+9
8090          Year=Year-1
8100       END IF
8110       Century=Year DIV 100
8120       Remainder=Year MOD 100
8130       Julian=146097*Century DIV 4+1461*Remainder DIV 4+(153*Month+2) DIV 5+D
ay+1721119
8140       Julian=Julian*86400
8150       IF Julian<2.08662912E+11 OR Julian>=2.143252224E+11 THEN Err
8160       RETURN Julian
8170 Err: OFF ERROR
8180       RETURN TIMEDATE
8190    FNEND
```

# APPENDIX F

# DATA ACQUISITION AND PLOTTING ROUTINE FOR WURMLINGER DYNAMIC CALIBRATION TESTS

## PROGRAM "HSDAR5-1"

The data acquisition program and plotting routine used for the dynamic propeller blade test performed during May 1984 has the following features:

Controls the operation of the HP6940B analogue subsystem;

Has utility graphics features for displaying acquired data;

Has a routine for calculating Fast Fourier Transforms of the data, and;

Has routines for calculating blade forces, etc. from blade strain gauge readings (the A matrix).

```
10   ! Program HSDAR5_1 /M. H. Edgecombe /84-05-17
20   ! High Speed Data Acquisition Routine for the HP 9836 desktop computer
30   ! and the HP 6940B multiprogrammer.
40   !
50   ! Hardware Configuration:
60   !     - 1 of HP Series 200 model 36 desktop computer (HP 9836)
70   !     - 6 of HP 98256 256K RAM memory boards installed in the 9836
80   !     - 1 of HP 98622A opt. 003 GP-IO interface (select code 12)
90   !
100  !     - 1 of HP 6940B multiprogrammer mainframes connected to the HP9836
110  !       via the HP 98622A GP-IO interface and opt. 003 cable.
120  !     - 1 of HP 69351B voltage regulator card installed in m/p slot 600
130  !     - 1 of HP 69602A timer/pacer card installed in m/p slot 400
140  !     - 1 of HP 69422A high speed a/d card installed in m/p slot 401
150  !     - 2 of HP 69336B high speed scanner cards installed in m/p slots 402
160  !       and 403
170  !
180  ! Operating System and Extensions:
190  !     - BASIC 2.0
200  !     - BASIC Extensions 2.1
210  !
220    OPTION BASE 1
230    INTEGER I,J,K,L,M,N,Nchnls!,Nrdgs,Nbytes,Range
240    INTEGER Period,Nscans,Form,Lines,Start_line
250    INTEGER V(8000,8) BUFFER,A(8000,8),Rdgs(1,8)
260    DIM Title$[80],Date$[12],Time$[12],Sig$(2,8)[9],File$[25],A_matrix(3,6)
270    INTEGER Nn
280    DIM X(0:1023,2),Y(0:1023,2),Ww(0:511,2),Mag(0:1023,21:28),B(0:10)
290    INTEGER Shuffle(0:1023,0:10),Shuffle_flag(0:10)
300    DATA -1.404E-2,-7.914E-3,4.934E-2,3.949E-3,2.470E-2,1.204E-2
310    DATA -7.688E-3,-1.690E-3,6.067E-2,1.679E-2,-6.203E-2,-2.299E-4
320    DATA -1.765E-1,-1.391E-3,1.791E-1,1.393E-2,1.217E-1,2.199E-2
330    READ A_matrix(*)
340   !
350    Scan_period=.1
360    Nchnls=8
370    Nrdgs=8000
380    Nwords=Nrdgs*Nchnls
390    Nbytes=Nwords*2
400    Form=18
410    DATA "  CENTRE ","    TE   ","    LE   ","  CENTRE "
420    DATA "    TE   ","    LE   "," SLIDING "," APPLIED "
430    DATA " BENDING ","  TORQUE "," BENDING ","  TORQUE "
440    DATA " BENDING ","  TORQUE ","  BLOCK  ","   LOAD  "
450    READ Sig$(*)
460  !
470    ASSIGN @Buffer TO BUFFER V(*);WORD
480    ASSIGN @Multiprogrammer TO 12;WORD
490   !
500    Timer_card=0
510    Ad_card=4096
520    Scanner_card0=8192
530    Scanner_card1=12288
540    Cw=-4096
550    Isl=128
560    Dte=64
570    Sye=32
580    Tme=16
590 Ctl_fmt:IMAGE #,W
600   !
610 Start:  !
620    IF TIMEDATE<2.09E+11 THEN GOSUB Set_time
630    Nscans=0
640   !
650 Driver:  !
660    OFF KEY
```

```
670    ON KEY 0 LABEL "START SCAN",3 GOTO Scan
680    ON KEY 1 LABEL "LIST DATA",3 GOTO List_data
690    ON KEY 2 LABEL "SAVE DATA",3 GOTO Save_data
700    ON KEY 5 LABEL "",3 GOTO Idle
710    ON KEY 6 LABEL "PLOT DATA",3 GOTO Graphics
720    ON KEY 7 LABEL "GET DATA",3 GOTO Get_data
730    ON KEY 8 LABEL "",3 GOTO Idle
740    ON KEY 9 LABEL "",3 GOTO Idle
750  !
760 Idle:GOSUB Display_time
770    GOTO Idle
780  !
790 Scan:  !
800    DISP "SCANNING EIGHT CHANNELS AT 16,000 CHANNELS PER SECOND"
810  !PRINT CHR$(12)
820  !GOSUB Print_header
830 Sample_loop:GOSUB Sample
840    Nscans=Nrdgs
850    PRINT "64,000 READINGS INPUT. END OF SCAN"
860    PRINT Nrdgs*8.0/(T2-T1);"  SAMPLES PER SECOND"
870    BEEP
880    GOTO Driver
890              ! I=Nscans
900              ! GOSUB Print_volts
910              ! IF Lines>=Form THEN GOSUB Print_header
920              ! WAIT Scan_period
930              ! GOTO Sample_loop
940   !
950 Sample:   !
960    DISABLE
970    RESET 12
980    Range=0          ! timer increment is 10^Range microseconds
990    Range=2^Range
1000   Period=31        ! time between channels is 2XPeriod*Range
1010   Start_channel=7
1020 !
1030 Sample_rate: !
1040   OUTPUT 12 USING Ctl_fmt;Cu+Sye
1050   OUTPUT 12 USING Ctl_fmt;Timer_card+3072+Range
1060   OUTPUT 12 USING Ctl_fmt;Timer_card+Period
1070 !
1080 Start_chan: !
1090   OUTPUT 12 USING Ctl_fmt;Cu+Sye
1100   OUTPUT 12 USING Ctl_fmt;Scanner_card1+2048+16          ! 2048=disabled
1110   OUTPUT 12 USING Ctl_fmt;Scanner_card0+Start_channel    ! enabled
1120 !
1130 Address_adc: !
1140   OUTPUT 12 USING Ctl_fmt;Cu+Isl+Sye+Tme
1150   CONTROL 12,3;Ad_card
1160 !
1170 Transfer: !
1180   T1=TIMEDATE
1190   TRANSFER @Multiprogrammer TO @Buffer;COUNT Nbytes,WAIT
1200 ! Busy:   STATUS @Buffer,10;Stat
1210 !         IF BIT(Stat,6) THEN Busy
1220   T2=TIMEDATE
1230 !
1240 Shut_down: !
1250   OUTPUT 12 USING Ctl_fmt;Cu+Sye+Dte
1260   OUTPUT 12 USING Ctl_fmt;Timer_card+Period
1270   OUTPUT 12 USING Ctl_fmt;Timer_card+3072
1280 !
1290 !
1300 Convert: !
1310   MAT V= V+(32768)
1320   MAT A= (2047)
```

```
1330   MAT A= V>A
1340   MAT A= A*(-4096)
1350   MAT V= V+A
1360   !
1370  !Nscans=Nscans+1
1380  !FOR I=1 TO 8
1390  ! Rdgs(Nscans,I)=V(1,I)
1400  !NEXT I
1410   !
1420   CONTROL @Buffer,5;1
1430   CONTROL @Buffer,4;1
1440   CONTROL @Buffer,3;1
1450  !IF Nscans>=500 THEN GOTO Driver
1460   !
1470   ENABLE
1480   RETURN
1490 !
1500 Graphics: !
1510   GCLEAR
1520   Sig=1
1530   Xmn=0
1540   Xmx=Nrdgs/2000
1550   Ymin=-10.250
1560   Ymax=10.250
1570  !
1580 G_loop:  !
1590   INPUT "ENTER NUMBER OF SIGNAL TO BE PLOTTED - SIG 21 TO 28 ARE FFT...",Si
g
1600   IF Sig<21 THEN
1610      INPUT "ENTER XMIN,XMAX...",Xmn,Xmx
1620      INPUT "ENTER YMIN,YMAX...",Ymin,Ymax
1630   ELSE
1640      INPUT "ENTER MAXIMUM FREQUENCY",Fmax
1650      INPUT "ENTER YMAX",Ymax
1660      Ymin=0
1670      Xmn=0
1680      Xmx=1024/2000
1690   END IF
1700   Xmin=2000*Xmn
1710   Xmax=2000*Xmx
1720  !
1730   PRINT CHR$(12)
1740   OFF KEY
1750   ON KEY 4 LABEL "",3 GOTO G_idle
1760   ON KEY 6 LABEL "Plot Calc",3 GOTO Odd_signals
1770   ON KEY 5 LABEL "New Signal",3 GOTO New_signal
1780   ON KEY 1 LABEL "Calculate",3 GOTO Force
1790   ON KEY 0 LABEL "New Plot",3 GOTO G_loop
1800   ON KEY 9 LABEL "EXIT",3 GOTO Exit
1810   ON KEY 7 LABEL "",3 GOTO G_idle
1820   ON KEY 8 LABEL "FFT",3 GOTO Fft
1830   GOSUB Plot
1840 G_idle:GOTO G_idle
1850  !
1860 New_signal:INPUT "ENTER NUMBER OF CHANNEL TO BE PLOTTED...",Sig
1870   GOTO Plot_wave_form
1880 Odd_signals:INPUT "ENTER NUMBER OF CALCULATED QUANTITY TO BE PLOTTED...",Si
g
1890  !
1900 Plot:  !
1910   DEG
1920   GINIT
1930   GRAPHICS ON
1940   FRAME
1950   VIEWPORT 15,130,15,95
```

```
1960   WINDOW Xmin,Xmax,Ymin,Ymax
1970   IF (Ymax-Ymin)>.3 AND Sig<21 THEN AXES 200,.2,Xmin,0,10,5
1980   IF (Ymax-Ymin)>.3 AND Sig>20 THEN AXES 256,.2,Xmin,0,8,5
1990   IF (Ymax-Ymin)<=.3 AND Sig<21 THEN AXES 200,.02,Xmin,0,10,5
2000   IF (Ymax-Ymin)<=.3 AND Sig>20 THEN AXES 256,.02,Xmin,0,8,5
2010  !
2020   LDIR 0
2030   LORG 3
2040   CSIZE 3.5
2050   MOVE Xmin+.01*(Xmax-Xmin),-.015*(Ymax-Ymin)
2060   IF Sig<21 THEN LABEL USING "K";Xmin/2000
2070   LORG 9
2080   MOVE Xmax,-.015*(Ymax-Ymin)
2090   IF Sig<21 THEN LABEL USING "K";Xmax/2000
2100  !
2110   CLIP OFF
2120   LORG 5
2130   MOVE Xmin+.5*(Xmax-Xmin),-.05*(Ymax-Ymin)
2140   IF Sig<21 THEN LABEL USING "K";"TIME (seconds)"
2150   IF Sig>20 THEN LABEL USING "K";"MAXIMUM FREQUENCY (Hz) "&VAL$(Fmax)
2160  !
2170   LORG 8
2180   MOVE Xmin-.015*(Xmax-Xmin),Ymin
2190   LABEL USING "K";Ymin
2200   MOVE Xmin-.015*(Xmax-Xmin),Ymax
2210   LABEL USING "K";Ymax
2220  !
2230   LDIR 90
2240   LORG 4
2250   MOVE Xmin-.06*(Xmax-Xmin),Ymin+.5*(Ymax-Ymin)
2260   IF Sig<9 THEN LABEL USING "K";Sig$(1,Sig)&Sig$(2,Sig)&" (volts)"
2270   IF Sig>20 THEN LABEL USING "K";Sig$(1,Sig-20)&Sig$(2,Sig-20)&"  FFT AMPLI
TUDE"
2280   IF Sig=9 THEN LABEL USING "K";"BENDING MOMENT (kN.m)"
2290   IF Sig=10 THEN LABEL USING "K";"SPINDLE TORQUE (kN.m)"
2300   IF Sig=11 THEN LABEL USING "K";"OUT OF PLANE FORCE (kN)"
2310   IF Sig=12 THEN LABEL USING "K";"RELATIVE RARIUS)"
2320   IF Sig=13 THEN LABEL USING "K";"RELATIVE CHORD"
2330  !
2340   LDIR 0
2350   LORG 6
2360   MOVE Xmin+.5*(Xmax-Xmin),Ymin+.95*(Ymax-Ymin)
2370   LABEL USING "K";Title$
2380   CLIP ON
2390  !
2400   LORG 5
2410 Plot_wave_form:  !
2420   IF Sig>20 THEN Plot_fft
2430   Mult=1
2440   IF Sig=8 THEN Mult=-1/.1366465
2450   IF Sig>8 THEN Odd_buggers
2460   MOVE Xmin,V(Xmin+1,Sig)*.005*Mult
2470   FOR I=Xmin+1 TO Xmax
2480      PLOT I,V(I,Sig)*.005*Mult,-1
2490   NEXT I
2500   RETURN
2510 !
2520 Plot_fft:!
2530           Nn_reduced=2^(9-R)
2540   MOVE 0,Mag(0,Sig)*.005
2550   FOR I=0 TO (Fmax/1024)*256*(1/Nn_reduced)
2560      PLOT I*(4096/Fmax)*(Nn_reduced),Mag(I,Sig)*.005,-1
2570   NEXT I
2580   RETURN
2590  !
2600 Odd_buggers:  !
```

```
2610   IF Sig>11 THEN Really_odd
2620   Sig=Sig-8
2630   MOVE Xmin+1,F(Sig,1)
2640   FOR I=1 TO Len
2650      PLOT Xmin+I,F(Sig,I),-1
2660   NEXT I
2670   RETURN
2680  !
2690 Really_odd:  !
2700   Sig=Sig-11
2710   MOVE Xmin+1,F(Sig,1)
2720   FOR I=1 TO Len
2730      PLOT Xmin+I,Pos(Sig,I),-1
2740   NEXT I
2750   RETURN
2760  !
2770 Exit:GCLEAR
2780   GOTO Driver
2790  !
2800 List_data:  !
2810   OFF KEY
2820   ON KEY 5 LABEL "CONT",3 GOTO List_start
2830   ON KEY 9 LABEL "EXIT",3 GOTO Driver
2840   ON KEY 6 LABEL " ",3 GOTO Idle
2850   ON KEY 7 LABEL " ",3 GOTO Idle
2860   ON KEY 8 LABEL " ",3 GOTO Idle
2870   Start_line=1
2880   !
2890 List_start:   !
2900   PRINT CHR$(12)
2910   IF Title$<>"" THEN
2920      PRINT Title$
2930      PRINT "  Phi =";Phi;"  Theta =";Theta;"    ";Time$;"  ";Date$
2940   END IF
2950  !
2960   GOSUB Print_header
2970   Lines=6
2980  !
2990   FOR I=Start_line TO Nscans
3000      GOSUB Print_volts
3010      IF Lines>=Form THEN New_page
3020   NEXT I
3030  !
3040 New_page:IF I<Nscans THEN Start_line=I+1
3050   GOTO Idle
3060  !
3070 Print_header:  !
3080   PRINT
3090   PRINT "       ";
3100   FOR I=1 TO 8
3110      PRINT Sig$(1,I);
3120   NEXT I
3130   PRINT
3140   PRINT "       ";
3150   FOR I=1 TO 8
3160      PRINT Sig$(2,I);
3170   NEXT I
3180   PRINT USING "/"
3190   Lines=5
3200   RETURN
3210  !
3220 Print_volts:  !
3230   PRINT USING "2X,DDD,2X,#";I
3240   FOR J=1 TO 8
3250      PRINT USING "X,MDD.DDD,1X,#";V(I,J)*.005
```

```
3260   NEXT J
3270   PRINT
3280   Lines=Lines+1
3290   RETURN
3300  !
3310 Save_data:  !
3320   Time$=FNTime$(TIMEDATE)
3330   Date$=FNDate$(TIMEDATE)
3340   DISP Time$,Date$;
3350   INPUT "  ENTER TEST TITLE (80 char. max.)...",Title$
3360   INPUT "ENTER LOADING ANGLE RELATIVE TO RADIAL DIRECTION...",Phi
3370   INPUT "ENTER LOADING ANGLE RELATIVE TO CIRCUMFERENTIAL DIRECTION...",Thet
a
3380   INPUT "ENTER NAME OF OUTPUT DATA FILE...",File$
3390   Rec=(80+40+10+10+2+Nrdgs*8*2)/256
3400   CREATE BDAT File$,Rec
3410   ASSIGN @Outfile TO File$
3420   OUTPUT @Outfile;Title$,Date$,Time$,Phi,Theta,Nscans,V(*)
3430   ASSIGN @Outfile TO *
3440   GOTO Driver
3450  !
3460 Get_data:  !
3470   INPUT "ENTER NAME OF DATA FILE TO BE READ...",File$
3480   ASSIGN @Infile TO File$
3490   ENTER @Infile;Title$,Date$,Time$,Phi,Theta,Nscans,V(*)
3500   ASSIGN @Infile TO *
3510   GOTO Driver
3520  !
3530 Set_time:  !
3540   INPUT "ENTER CURRENT DATE (DD MMM YYYY)...",Date$
3550   SET TIMEDATE FNDate(Date$)
3560   INPUT "ENTER CURRENT TIME (HH:MM:SS)...",Time$
3570   SET TIME FNTime(Time$)
3580   RETURN
3590  !
3600 Display_time:  !
3610   DISP FNTime$(TIMEDATE),FNDate$(TIMEDATE)
3620   RETURN
3630  !
3640 Force:  !
3650   Corr_flag=0
3660   DISABLE
3670   Epsilon=1.E-6
3680   Len=Xmax-Xmin
3690   ON ERROR GOTO Error_routine
3700   DEALLOCATE F(*),W(*),Pos(*),Input_force(*)
3710   OFF ERROR
3720   ALLOCATE F(3,Len),W(6,Len),Pos(2,Len),Input_force(Len)
3730  !
3740   Scale_factor=-1/.1366
3750   K=1
3760   FOR I=Xmin TO Xmax-1
3770      FOR J=1 TO 6
3780         W(J,K)=V(I,J)
3790      NEXT J
3800      Input_force(K)=Scale_factor*V(I+Time_shift,8)
3810      K=K+1
3820   NEXT I
3830  !
3840   IF Corr_flag=0 THEN MAT F= A_matrix*W
3850   Z0=1.5*.34
3860   Cross_sum=0
3870   F_sum=0
3880   Input_force_sum=0
3890   FOR I=1 TO Len
3900      IF ABS(F(3,I))<Epsilon THEN 3960
```

```
3910       Pos(1,I)=F(1,I)/F(3,I)+Z0
3920       Pos(2,I)=F(2,I)/F(3,I)
3930       Cross_sum=Cross_sum+F(3,I)*Input_force(I)
3940       F_sum=F_sum+F(3,I)*F(3,I)
3950       Input_force_sum=Input_force_sum+Input_force(I)*Input_force(I)
3960    NEXT I
3970    Cross_corr=(Cross_sum)/SQR(F_sum*Input_force_sum)
3980   !
3990    PRINT USING "73A,MD.DDD";"CROSS CORRELATION COEFFICIENT BETWEEN INPUT FOR
CE AND CALCULATED FORCE = ",Cross_corr
4000    PRINT "TIME SHIFT =",Time_shift
4010    PRINT
4020    Corr_flag=1
4030    Time_shift$=""
4040    INPUT "INPUT TIME SHIFT",Time_shift$
4050    IF Time_shift$="" THEN
4060       Time_shift=0
4070       ENABLE
4080       GOTO G_idle
4090    ELSE
4100       Time_shift=VAL(Time_shift$)
4110       GOTO Force
4120    END IF
4130    BEEP
4140    ENABLE
4150    GOTO G_idle
4160   !
4170 Error_routine:    !
4180    OFF ERROR
4190    IF ERRN=142 THEN GOTO 3710
4200    DISP ERRM$
4210    PAUSE
4220    GOTO 3700
4230 Fft:  !
4240    Nn=512
4250    INPUT "ENTER # OF POINTS IN FFT (MUST BE A POWER OF 2)",Nn
4260    R=INT((LOG(Nn)/LOG(2))+1.E-6)
4270    IF INT(2^R+.005)<>Nn THEN Fft
4280    FOR K=0 TO Nn-1
4290       Y(K,1)=V(K+Xmin,Sig)
4300       Y(K,2)=0
4310    NEXT K
4320 Re_order:!
4330    IF Shuffle_flag(R) THEN Next_part
4340    FOR K=0 TO Nn-1
4350       I=-1
4360       L=K
4370       I=I+1
4380       Mm=L*.5
4390       IF 2*INT(Mm)=L THEN
4400          L=Mm
4410          B(I)=0
4420          GOTO 4460
4430       END IF
4440       L=INT(Mm)
4450       B(I)=1
4460       IF L>0 THEN 4370
4470       FOR J=I+1 TO R-1
4480          B(J)=0
4490       NEXT J
4500       I=R-1
4510       C=0
4520       FOR J=0 TO I
4530          C=C+B(J)*2^(I-J)
4540       NEXT J
4550       Shuffle(K,R)=C
```

```
4560   NEXT K
4570   Shuffle_flag(R)=1
4580 Next_part:!
4590   FOR K=0 TO Nn-1
4600      X(Shuffle(K,R),1)=Y(K,1)
4610      X(Shuffle(K,R),2)=Y(K,2)
4620   NEXT K
4630   RAD
4640   FOR S=1 TO R
4650      L=2^(S-1)
4660      P=2^(R-S)
4670      Temp1=-P*2*PI*(1/Nn)
4680      FOR K=0 TO L-1
4690         Wu(K,1)=COS(Temp1*K)
4700         Wu(K,2)=SIN(Temp1*K)
4710      NEXT K
4720            !
4730      FOR I=0 TO Nn-2*L STEP 2*L
4740         FOR K=0 TO L-1
4750            J=I+K
4760            Mm=J+L
4770            R1=X(Mm,1)*Wu(K,1)-X(Mm,2)*Wu(K,2)
4780            R2=X(Mm,1)*Wu(K,2)+X(Mm,2)*Wu(K,1)
4790            X(Mm,1)=X(J,1)-R1
4800            X(Mm,2)=X(J,2)-R2
4810            X(J,1)=X(J,1)+R1
4820            X(J,2)=X(J,2)+R2
4830         NEXT K
4840      NEXT I
4850   NEXT S
4860     !
4870 Fold_over:!
4880   Inverse=2/Nn
4890   FOR K=1 TO (Nn/2)-1
4900      Mag(K,Sig+20)=Inverse*SQR(X(K,1)*X(K,1)+X(K,2)*X(K,2))
4910   NEXT K
4920   Mag(0,Sig+20)=SQR(X(0,1)*X(0,1)+X(0,2)*X(0,2))*1/Nn
4930   Mag(Nn/2,Sig+20)=SQR(X(Nn/2,1)*X(Nn/2,1)+X(Nn/2,2)*X(Nn/2,2))*1/Nn
4940          !
4950   BEEP
4960   GOTO G_loop
4970   END
4980  !
4990  !
5000   DEF FNTime$(Now)
5010      Now=INT(Now) MOD 86400
5020      H=Now DIV 3600
5030      M=Now MOD 3600 DIV 60
5040      S=Now MOD 60
5050      OUTPUT T$ USING "#,ZZ,K";H,":",M,":",S
5060      RETURN T$
5070   FNEND
5080  !
5090   DEF FNTime(T$)
5100      ON ERROR GOTO Err
5110      ENTER T$;H,M,S
5120      RETURN (3600*H+60*M+S) MOD 86400
5130 Err: OFF ERROR
5140      RETURN TIMEDATE MOD 86400
5150   FNEND
5160  !
5170   DEF FNDate$(Seconds)
5180      DATA JAN,FEB,MAR,APR,MAY,JUN,JUL,AUG,SP,OCT,NOV,DEC
5190      DIM Month$(1:12)[3]
5200      READ Month$(*)
5210  !
```

CANMAR

**CANADIAN MARINE DRILLING LIMITED**

**MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS**

**TITLE:**

**"HSDAR5-1"**

**APPENDIX F**

```
5220       Julian=Seconds DIV 86400-1721119
5230       Year=(4*Julian-1) DIV 146097
5240       Julian=(4*Julian-1) MOD 146097
5250       Day=Julian DIV 4
5260       Julian=(4*Day+3) DIV 1461
5270       Day=(4*Day+3) MOD 1461
5280       Day=(Day+4) DIV 4
5290       Month=(5*Day-3) DIV 153
5300       Day=(5*Day-3) MOD 153
5310       Day=(Day+5) DIV 5
5320       Year=100*Year+Julian
5330       IF Month<10 THEN
5340          Month=Month+3
5350       ELSE
5360          Month=Month-9
5370          Year=Year+1
5380       END IF
5390       OUTPUT D$ USING "#,ZZ,X,3A,X,4Z";Day,Month$(Month),Year
5400       RETURN D$
5410    FNEND
5420   !
5430    DEF FNDate(Dmy$)
5440       DATA JAN,FEB,MAR,APR,MAY,JUN,JUL,AUG,SEP,OCT,NOV,DEC
5450       DIM Month$(1:12)[3]
5460       READ Month$(*)
5470   !
5480       ON ERROR GOTO Err
5490       I$=Dmy$&"    "
5500       ENTER I$ USING "DD,4A,5D,";Day,M$,Year
5510       IF Year<100 THEN Year=Year+1900
5520       FOR I=1 TO 12
5530          IF POS(M$,Month$(I)) THEN Month=I
5540       NEXT I
5550       IF Month=0 THEN Err
5560       IF Month>2 THEN
5570          Month=Month-3
5580       ELSE
5590          Month=Month+9
5600          Year=Year-1
5610       END IF
5620       Century=Year DIV 100
5630       Remainder=Year MOD 100
5640       Julian=146097*Century DIV 4+1461*Remainder DIV 4+(153*Month+2) DIV 5+D
ay+1721119
5650       Julian=Julian*86400
5660       IF Julian<2.08662912E+11 OR Julian>=2.143252224E+11 THEN Err
5670       RETURN Julian
5680 Err: OFF ERROR
5690       RETURN TIMEDATE
5700    FNEND
```

# APPENDIX G
# COMPUTER LISTING OF "ANALYZE"

## PROGRAM "ANALYZE"

This program is the basic data analysis program in that it displays and performs analysis on the data file generated by "RLDAR-7". "RLDAR-7" acquired the test data on-board the vessel during the field test period in June/July 1984.

The functions contained within the program are:

- Plotting on the screen of any time segment of any of the 35 channels of data;
- Allow the user to choose and vary the 'y' scale of the data which is displayed in engineering units;
- Can overlay additional channels of data on the same screen;
- Using the knob, a cursor can move along the displayed data and indicate the time and y value of the data. Via a soft key can one write the y value onto the screen;
- Can dump the image on the screen onto the printer;
- Can choose a display mode such that the top half of the screen displays one channel of data while the lower half displays another channel;
- Can design a digital low pass filter and perform filtering on any channel;
- Can use the [A] matrix to calculated force, bending moment and spindle torque from the blade strain gauge data;
- Can optionally subtract the hydrodynamic baseline from the strain gauge data prior to calculating blade force, etc;
- Calculates radial and circumferential load location from blade force, bending moment and spindle torque. In the case of filtered data, the filtered locations are calculated using filtered input rather than filtering the location data directly;
- Perform a Fourier Transform of any channel of data;

- Various utility functions including printing a list of channel assignments, and;
- Calculate the x-y location of the tail shaft from individual probe readings.

```
10     !    ANALYSIS OF ICE PROPELLER INTERACTION DATA
20     !
30     !    WRITTEN BY: DOUG MONTGOMERY
40     !    DATE: MAY 22, 1984
50     !    VERSION: 1.0
60     !
70     !    MODIFIED BY:PAUL SPENCER
80     !    DATE:JUNE 25 1984
90     !    VERSION:ANALYZE2
100    !    REASON:TO MATCH DATA AQUISITION PROGRAMME "RLDAR4"
110    !
120    !    MODIFIED BY:
130    !    DATE:
140    !    VERSION:
150    !    REASON:
160    !
170    !
180      OPTION BASE 1
190      GCLEAR
200      Total_channels=35
210      INTEGER Signals(7000,18)       ! 7 SECONDS OF DATA
220      INTEGER Baseline(18)           ! BASELINE VALUES OF CHANNELS
230      DIM Channel_desc$(18)[30]      ! DESCRIPTION OF DATA CHANNELS
240      ALLOCATE Calc_chanl_desc$(19:Total_channels)[35]      ! DESCRIPTION OF
 CALCULATED CHANNELS
250      REAL Slope(18)                 ! 'M' OF DATA CHANNELS
260      REAL Slope_16(2)               ! 2 SLOPES FOR CHANNEL 16
270      REAL Offset(18)                ! 'b' OF DATA CHANNELS
280      INTEGER Current_record         ! CURRENT PLOTTING RECORD
290      INTEGER Rpm(0:50)              ! SHAFT SPEED BETWEEN PULSES IN R.P.M.
300      INTEGER Rpm_pulse(0:50)        ! RECORD NUMBER OF PULSES
310      INTEGER Numb_of_pulse          ! NUMBER OF PULSES
320      INTEGER Rpm_channel            ! CHANNEL # OF SHAFT
330      INTEGER Channels               ! NUMBER OF CHANNELS OF DATA
340      INTEGER Shaft_speed            ! CURRENT SHAFT SPEED IN R.P.M.
350      INTEGER Channel_no             ! CURRENT CHANNEL BEING PLOTTED
360      INTEGER N_channels             ! NUMBER OF CHANNELS OF DATA ON DISC
370      REAL Nscans                    ! NUMBER OF SCANS ON DISC
380      REAL Scan_rate                 ! SCAN RATE/SCEOND FROM DISC
390      REAL Int_data                  ! INTERRUPT DATA - WHICH CHANNEL
400      REAL Int_pointer               ! INTERRUPT POINTER - WHERE IN DATA
410      ALLOCATE INTEGER K(7000,19:Total_channels)   ! CALCULATED DATA MATRIX
420      ALLOCATE REAL Scale_factor(19:Total_channels) ! SCALE FACTOR FOR CALCUL
ATED DATA MATRIX 'K' ABOVE
430      REAL A(3,6)                    ! THE CURRENT 'A' MATRIX IN USE
440      REAL A_matrix(2,3,6)           ! ALL OF THE 'A' MATRIX USED IN CONVERT
ING THE STRAIN GUAGE READINGS TO FORCES
450      REAL Mean(2,6)                 ! MIDPOINTS FOR HYDRO-DYNAMIC CORRECTIO
N
460      DIM Title$[80]                 ! TITLE READ FROM DATA DISC
470      DIM Dates$[12]                 ! DATE READ FROM DATA DISC
480      DIM Times$[12]                 ! TIME READ FROM DATA DISC
490      ALLOCATE Units$(Total_channels)[6]            !UNITS OF ENGINEERING
CONVERTED AQUIRED CHANNELS
500      ALLOCATE REAL Pre_filter(-50:50) ! CALCULATED PRE-FILTER COEFFICIENTS
510      ALLOCATE REAL Post_filter(-50:50) ! CALCULATED POST-FILTER COEFFICIENTS
520      INTEGER Filter_size            ! SIZE OF CURRENT FILTER BEING USED
530      REAL Ripple                    ! RIPPLE dB FOR FILTER DESIGN
540      REAL Rejection                 ! REJECTION dB FOR FILTER DESIGN
550      REAL Upper_limit               ! UPPER LIMIT OF FREQUENCY FOR FILTER D
ESIGN
560      REAL Lower_limit               ! LOWER LIMIT OF FREQUENCY FOR FILTER D
ESIGN
570      REAL Because
580      INTEGER E1,E2                  ! DISPLACEMENT TRANSDUCER ANGLES
590      INTEGER Shuffle1(1:12)         ! TEMP. SHUFFLE MATRIX FOR FFT
```

```
600      INTEGER I,J,R,Q,Nn,S,L,Mm          ! MISC. VARIABLES FOR FFT
610      REAL Temp1,R1,R2,Inverse           ! MISC. VARIABLES FOR FFT
620      INTEGER G(1:6,1:7001)              ! STRAIN GUAGE READINGS
630      INTEGER First_tape_read
640      REAL Prop_data(1:3)
650      REAL Times(1:3)
660   !
670      Channels=18                        ! NUMBER OF DATA CHANNELS READ FROM DIS
C
680      Nscans=7000
690      Channel_no=1                       ! DEFAULT CHANNEL FIRST PLOTTED
700      Rpm_channel=15                     ! CHANNEL NUMBER OF THE SHAFT SENSOR
710      E1=90                              ! ANGLE OF FORWARD DISPLACEMENT PROBES
720      E2=45                              ! ANGLE OF AFT DISPLACEMENT PROBES
730      First_tape_read=1
740      INTEGER Screen_buffer(12480)
750      !
760      ! CALCULATED QUANTITES CHANNEL DESCRIPTION
770      !
780      Calc_chanl_desc$(19)="BENDING MOMENT"
790      Calc_chanl_desc$(20)="SPINDLE TORQUE"
800      Calc_chanl_desc$(21)="FORCE"
810      Calc_chanl_desc$(22)="RADIAL LOCATION"
820      Calc_chanl_desc$(23)="CIRCUMFERENTIAL LOCATION"
830      Calc_chanl_desc$(26)="FORCE (FILTERED)"
840      Calc_chanl_desc$(25)="SPINDLE TORQUE (FILTERED)"
850      Calc_chanl_desc$(24)="BENDING MOMENT (FILTERED)"
860      Calc_chanl_desc$(27)="RADIAL LOCATION (FILTERED)"
870      Calc_chanl_desc$(28)="CIRCUMFERENTIAL LOCATION (FILTERED)"
880      Calc_chanl_desc$(29)="AFT HORIZONTAL"
890      Calc_chanl_desc$(30)="AFT VERTICAL"
900      Calc_chanl_desc$(31)="FORWARD HORIZONTAL"
910      Calc_chanl_desc$(32)="FORWARD VERTICAL"
920      Calc_chanl_desc$(33)="FFT"
930      Calc_chanl_desc$(34)="SHAFT SPEED"
940      Calc_chanl_desc$(35)="FILTERED CHANNEL DATA"
950   !
960   ! CHANNEL DESCRIPTION FOR AQUIRED CHANNELS
970   !
980      Channel_desc$(1)="CENTRE BENDING"
990      Channel_desc$(2)="TRAILING EDGE TORQUE"
1000     Channel_desc$(3)="LEADING EDGE BENDING"
1010     Channel_desc$(4)="CENTRE TORQUE"
1020     Channel_desc$(5)="TRAILING EDGE BENDING"
1030     Channel_desc$(6)="LEADING EDGE TORQUE"
1040     Channel_desc$(7)="SLIDING BLOCK FORCE"
1050     Channel_desc$(8)="SHAFT THRUST"
1060     Channel_desc$(9)="SHAFT TORQUE"
1070     Channel_desc$(10)="SERVO OIL PRESSURE"
1080     Channel_desc$(11)="AFT PORT PROBE"
1090     Channel_desc$(12)="AFT TOP PROBE"
1100     Channel_desc$(13)="FUEL RACK"
1110     Channel_desc$(14)="FWD STRB PROBE"
1120     Channel_desc$(15)="SHAFT RATE PULSE"
1130     Channel_desc$(16)="PROPELLER PITCH"
1140     Channel_desc$(17)="SHIP SPEED"
1150     Channel_desc$(18)="RUDDER ANGLE"
1160     !
1170     !ENGINEERING UNITS FOR ALL CHANNELS (>18 ARE DERIVED QUANTITIES)
1180     !
1190     Units$(1)="  MPa"
1200     Units$(2)="  MPa"
1210     Units$(3)="  MPa"
1220     Units$(4)="  MPa"
1230     Units$(5)="  MPa"
1240     Units$(6)="  MPa"
```

```
1250     Units$(7)="  kN"
1260     Units$(8)="  kN"
1270     Units$(9)="  kN.m"
1280     Units$(10)="  bar"
1290     Units$(11)="  mm"
1300     Units$(12)="  mm"
1310     Units$(13)="  mm"
1320     Units$(14)="  mm"
1330     Units$(15)="  volt"
1340     Units$(16)="  deg"
1350     Units$(17)="  m/s"
1360     Units$(18)="  deg"
1370     !
1380     Units$(19)="  kN.m"
1390     Units$(20)="  kN.m"
1400     Units$(21)="  kN"
1410     Units$(22)="  m"
1420     Units$(23)="  m"
1430     Units$(24)="  kN.m"
1440     Units$(25)="  kN.m"
1450     Units$(26)="  kN"
1460     Units$(27)="  m"
1470     Units$(28)="  m"
1480     Units$(29)="  mm"
1490     Units$(30)="  mm"
1500     Units$(31)="  mm"
1510     Units$(32)="  mm"
1520     Units$(34)="  RPM"
1530     Units$(35)="     "
1540     !
1550             ! 3x6 MATRIX FOR CONVERTING STRAIN GUAGE READINGS INTO FORCES
1560             !A MATRIX ALL CHANNELS
1570     DATA -1.404E-2,-7.914E-3,4.934E-2,3.949E-3,2.470E-2,1.204E-2
1580     DATA +7.688E-3,+1.690E-3,-6.067E-2,-1.679E-2,+6.203E-2,+2.299E-4
1590     DATA -1.765E-1,-1.391E-3,1.791E-1,1.393E-2,1.217E-1,2.199E-2
1600     !
1610     ! A MATRIX FOR CHANNEL 6 DEAD
1620     !
1630     DATA -7.957E-3,-6.228E-3,2.698E-2,3.538E-3,3.981E-2,0!BENDING MOMENT
1640     DATA +7.727E-3,+1.628E-3,-6.070E-2,-1.702E-2,+6.193E-2,0!SPINDLE TORQUE
1650     DATA -1.607E-1,-1.353E-2,1.281E-1,1.299E-2,1.545E-1,0! FORCE
1660     READ A_matrix(*)
1670     !
1680     !
1690     !A MATRIX GENERATED BY MATRIXTEST ASSUMS THAT VOLTAGE IS IN mV
1700     !BUT 6940b LSB =5mV.
1710     !IN MATRIXTEST UNIT OF LENGTH IS mm SO TO USE M THE 1st &2nd ROW
1720     !IN THE READ STATMENT HAVE BEEN MULTIPLIED BY 10^-3
1730     !HAVE MUTIPLIED TORQUE ROW BY -1 TO MAKE ANTICLOCKWISE TORQUE ,
1740     !LOOKING FROM ABOVE BLADE,+ve
1750     !
1760     MAT A_matrix= A_matrix*(5)
1770   !
1780   ! SCALE FACTORS FOR CALCULATED VALUES - CONVERSION TO INTEGERS
1790   !
1800     DATA 25,25,25,1000,1000,25,25,25,1000,1000,1000,1000,1000,1000,100,10,1
1810     READ Scale_factor(*)
1820     !
1830     DATA .226,.0615,.226,.0615,.226,.0615,1.68,5.76,.462,.1406
1840     DATA .000635,.000635,.0181,.000635,.005,.0175,.0257,.0798
1850     READ Slope(*) !TO CONVERT AQUIRED CHANNELS TO ENGINEERING UNITS
1860     !
1870     DATA 0,0,0,0,0,0,0,0,0,0
1880     DATA .164,.263,.515,.286,0,0,0,0
1890     READ Offset(*)!TO CONVERT AQUIRED CHANNELS TO ENGINEERING UNITS
1900     !
```

```
1910     REAL Vert_scale(0:14)        !"NICE" Y SCALE VALUES
1920     DATA 0,1.0,1.25,1.5,1.75,2.0,2.5,3,4,5,6,7,8,9,10
1930     READ Vert_scale(*)
1940  !
1950  !                  MAINLINE PROCESSING
1960  !
1970     PRINTER IS 1
1980     PRINT CHR$(12)
1990     Today$=DATE$(TIMEDATE)
2000     IF Today$[8,11]="1900" THEN GOSUB Set_time
2010     GOSUB Mainline
2020     GRAPHICS OFF
2030     GCLEAR
2040     PRINTER IS 1
2050     STOP
2060  !
2070  ! ===============================================================
2080  !  MAINLINE
2090  ! ===============================================================
2100 Mainline:    !
2110     INPUT "READ DATA FROM DISC, OR MAG. TAPE?  D or T",R$
2120     IF R$[1,1]="T" THEN
2130        GOSUB Read_mag_tape
2140     ELSE
2150        GOSUB Read_data
2160     END IF
2170     GOSUB Rpm_calculate
2180     Main_exit=0
2190     ON KNOB .1,9 GOSUB Move_cursor
2200     GOSUB Main_keys
2210     GOTO Quick_look
2220 Main_loop:     !
2230     IF NOT Main_exit THEN Main_loop
2240     GCLEAR
2250     GRAPHICS OFF
2260     RETURN
2270  !
2280  ! ===============================================================
2290  !   MAIN KEYS
2300  ! ===============================================================
2310 Main_keys:    !
2320     ON KEY 0 LABEL "YMAX Inc/Dec" GOTO Ymaxinc
2330     ON KEY 10 GOTO Ymaxdec
2340     ON KEY 5 LABEL "YMIN Inc/Dec" GOTO Ymininc
2350     ON KEY 15 GOTO Ymindec
2360     ON KEY 1 LABEL "CHANNEL LIST" GOSUB Channel_list
2370     ON KEY 6 LABEL "DUMP/EXPAND" GOSUB Dump_graphics
2380     ON KEY 16 GOSUB Dump_expanded
2390     ON KEY 2 LABEL "ADD CHANNEL" GOTO Select_channel
2400     ON KEY 7 LABEL "VIEW/SPLITVIEW" GOTO New_plot
2410     ON KEY 17 GOTO Two_plot
2420     ON KEY 3 LABEL "FILTER/DESIGN" GOSUB Digital_filter
2430     ON KEY 13 GOSUB Filter_design
2440     ON KEY 8 LABEL "CALCULATE" GOSUB Calculate
2450     ON KEY 4 LABEL "LABEL UP/DOWN" GOSUB Label_up
2460     ON KEY 14 GOSUB Label_down
2470     ON KEY 9 LABEL "FFT/STATS" GOSUB Fft
2480     ON KEY 19 GOSUB Statistics
2490     RETURN
2500  !
2510  ! ===============================================================
2520  !  MAIN EXIT
2530  ! ===============================================================
2540 Main_exit:    !
2550     Main_exit=1
2560     RETURN
```

```
2570  !
2580  ! ============================================================
2590  !   MOVE CURSOR
2600  ! ============================================================
2610 Move_cursor:    !
2620      I$=CHR$(129)
2630      N$=CHR$(128)
2640      IF Channel_no>28 AND Channel_no<33 THEN RETURN
2650      PEN 0
2660      IF Channel_no=33 THEN GOSUB Channel_no_33
2670      IF Channel_no=33 THEN RETURN
2680      IF Channel_no>18 THEN
2690         MOVE Current_record*Corr_factor,K(Current_record,Channel_no)/Scale_f
actor(Channel_no)
2700      ELSE
2710         MOVE Current_record*Corr_factor,Signals(Current_record,Channel_no)*S
lope(Channel_no)+Offset(Channel_no)
2720      END IF
2730      LABEL "+"
2740      Knob_value=KNOBX*MAX(.5,ABS(Xmn-Xmx))
2750      Current_record=Current_record+Knob_value
2760      Xmin_temp=MAX(1,INT(Xmin/Corr_factor))
2770      Xmax_temp=MIN(INT(Xmax/Corr_factor),Nscans)
2780      IF Current_record<=Xmin_temp THEN Current_record=Xmax_temp
2790      IF Current_record>Xmax_temp THEN Current_record=Xmin_temp
2800      IF Channel_no>18 THEN
2810         Temp_disp=K(Current_record,Channel_no)/Scale_factor(Channel_no)
2820         MOVE Current_record*Corr_factor,Temp_disp
2830         IF NOT Calculate_flag THEN DISP USING "K";I$,"    ",(Current_record)*
Corr_factor/1000," s  ",Temp_disp,Units$(Channel_no)," ",N$
2840      ELSE
2850         Temp_disp=Signals(Current_record,Channel_no)*Slope(Channel_no)+Offse
t(Channel_no)
2860         MOVE Current_record*Corr_factor,Temp_disp
2870         IF NOT Calculate_flag THEN DISP USING "K";"      ",I$,(Current_record
)*Corr_factor/1000," s  ",Temp_disp,Units$(Channel_no)," ",N$
2880      END IF
2890      PEN 0
2900      LABEL "+"
2910      PEN 1
2920      RETURN
2930  ! ============================================================
2940  !   MOVE CURSOR ROUTINE FOR CHANNEL NO 33 (FFT)
2950  ! ============================================================
2960 Channel_no_33: !
2970      I$=CHR$(129)
2980      N$=CHR$(128)
2990      MOVE Current_value*Scan_rate/Nn,K(Fft_min+1+Current_value,33)/Scale_fac
tor(33)
3000      LABEL "+"
3010      Knob_value=KNOBX*MAX(Max_frequency*.1,1)
3020      Current_value=Current_value+SGN(Knob_value)
3030      IF Current_value<0 THEN Current_value=Current_value+INT(.5+Max_frequenc
y*Nn/Scan_rate)
3040      IF Current_value>INT(.5+Max_frequency*Nn/Scan_rate) THEN Current_value=
Current_value-INT(.5+Max_frequency*Nn/Scan_rate)
3050      MOVE Current_value*Scan_rate/Nn,K(Fft_min+1+Current_value,33)/Scale_fac
tor(33)
3060 DISP USING "5A,A,DDD.D,5A,DDD.D,3A,A";"      ",I$,INT(.5+Current_value*Scan_
rate/Nn)," Hz  ",K(Fft_min+1+Current_value,33)/Scale_factor(33)," % ",N$
3070      PEN 0
3080      LABEL "+"
3090      PEN 1
3100      RETURN
3110  ! ============================================================
3120  !   Y MAX INCREASE
```

```
3130  ! ============================================================
3140 Ymaxinc:     !
3150      IF Channel_no>28 AND Channel_no<34 THEN Main_loop
3160      IF I_ymax<14 THEN
3170         I_ymax=I_ymax+1
3180      ELSE
3190         I_ymax=2
3200         Power_ymax=Power_ymax+1
3210      END IF
3220      GOTO Plot_set_up
3230  !
3240  ! ============================================================
3250  !   Y MAX DECREASE
3260  ! ============================================================
3270 Ymaxdec:     !
3280      IF Channel_no>28 AND Channel_no<34 THEN Main_loop
3290      IF I_ymax>1 THEN
3300         I_ymax=I_ymax-1
3310      ELSE
3320         I_ymax=13
3330         Power_ymax=Power_ymax-1
3340      END IF
3350      GOTO Plot_set_up
3360  !
3370  ! ============================================================
3380  !   Y MIN DECREASE
3390  ! ============================================================
3400 Ymindec:     !
3410      IF Channel_no>28 AND Channel_no<34 THEN Main_loop
3420      IF I_ymin<14 THEN
3430         I_ymin=I_ymin+1
3440      ELSE
3450         I_ymin=2
3460         Power_ymin=Power_ymin+1
3470      END IF
3480      GOTO Plot_set_up
3490  !
3500  ! ============================================================
3510  !   Y MIN INCREASE
3520  ! ============================================================
3530 Ymininc:     !
3540      IF Channel_no>28 AND Channel_no<34 THEN Main_loop
3550      IF I_ymin>1 THEN
3560         I_ymin=I_ymin-1
3570      ELSE
3580         I_ymin=13
3590         Power_ymin=Power_ymin-1
3600      END IF
3610      GOTO Plot_set_up
3620  !
3630  ! ============================================================
3640  !   PAGE HEADER
3650  ! ============================================================
3660 Page_header:     !
3670      Today$=DATE$(TIMEDATE)
3680      Time_today$=TIME$(TIMEDATE)
3690      RETURN
3700  !
3710  ! ============================================================
3720  !   SET TIME
3730  ! ============================================================
3740 Set_time:     !
3750      INPUT "ENTER DATE IN FORMAT DD MMM YYYY",Input_date$
3760      INPUT "ENTER TIME IN FORMAT HH:MM:SS",Input_time$
3770      SET TIMEDATE DATE(Input_date$)+TIME(Input_time$)
3780      RETURN
```

```
3790  !
3800  ! ==============================================================
3810  !   NUMERICAL OUTPUT
3820  ! ==============================================================
3830 Numerical_op:     !
3840      PRINTER IS 701
3850      PRINT " "
3860      PRINT " "
3870      PRINTER IS 1
3880      RETURN
3890  !
3900  ! ==============================================================
3910  !   CHANNEL LIST
3920  ! ==============================================================
3930 Channel_list:     !
3940      PRINTER IS 1
3950      INPUT "HARDCOPY OF CHANNEL LIST (Y OR N)",Y$
3960      IF Y$="Y" OR Y$="y" THEN
3970         PRINTER IS 701
3980         PRINT ""
3990         PRINT "                 "
4000         PRINT "




                "
4010      END IF
4020      PRINT "  TABLE OF CHANNEL DESCRIPTIONS"
4030      PRINT "--------------------------------"
4040      PRINT ""
4050      PRINT "      AQUIRED CHANNELS"
4060      PRINT ""
4070      FOR I=1 TO 18
4080         PRINT I,Channel_desc$(I),TAB(50),Units$(I)
4090      NEXT I
4100      PRINT ""
4110      PRINT "     CALCULATED QUANTITIES"
4120      PRINT ""
4130      FOR I=19 TO Total_channels
4140         PRINT I,Calc_chanl_desc$(I),TAB(50),Units$(I)
4150      NEXT I
4160      IF Y$="Y" OR Y$="y" THEN PRINT CHR$(12)
4170      PRINTER IS 1
4180      RETURN
4190  !
4200  ! ==============================================================
4210  !   FFT
4220  ! ==============================================================
4230 Fft:     !
4240      Nn=512
4250      INPUT "ENTER # OF POINTS IN FFT (MUST BE A POWER OF 2,MAXIMUM OF 4096)"
,Nn
4260      R=INT((LOG(Nn)/LOG(2))+1.E-6)
4270      IF (Nn-1+Xmin+1)>7000 THEN
4280         BEEP
4290         DISP "SELECTED FFT POINTS EXTEND BEYOND END OF DATA :SELECT FFT AGAI
N"
4300         RETURN
4310      END IF
4320      IF Nn<1 OR Nn>4096 THEN Fft
4330      IF INT(2^R+.005)<>Nn THEN Fft
4340      ALLOCATE INTEGER Shuffle2(0:Nn-1)
4350      ALLOCATE REAL Y(0:Nn-1)
4360      ALLOCATE REAL Y2(0:Nn-1)
4370      ALLOCATE REAL Wu(0:2048,1:2)           ! TEMP. MATRIX FOR FFT
```

```
4380      Fft_no=Channel_no
4390      Fft_min=Xmin
4400      MAT Y2= (0)
4410      DISP "CALCULATING FFT, PLEASE WAIT"
4420      IF Channel_no>18 THEN
4430         FOR Q=0 TO Nn-1
4440            Y(Q)=K(Q+Xmin+1,Channel_no)
4450         NEXT Q
4460      ELSE
4470         FOR Q=0 TO Nn-1
4480            Y(Q)=Signals(Q+Xmin+1,Channel_no)
4490         NEXT Q
4500      END IF
4510      Fft_units=0
4520      IF Units AND Channel_no<19 THEN
4530         MAT Y= Y*(Slope(Channel_no))
4540         MAT Y= Y-(Offset(Channel_no))
4550         Fft_units=Units
4560      END IF
4570      Array_mean=SUM(Y)/SIZE(Y,1)
4580      MAT Y= Y-(Array_mean)
4590      FOR I=1 TO R
4600         Shuffle1(I)=2^(I-1)
4610      NEXT I
4620      FOR I=0 TO (Nn/4-1)
4630         FOR J=1 TO R
4640            Shuffle2(I)=Shuffle2(I)+Shuffle1(J)*BIT(I,R-J)
4650         NEXT J
4660         Shuffle2(I+Nn/4)=Shuffle2(I)+2
4670         Shuffle2(I+Nn/2)=Shuffle2(I)+1
4680         Shuffle2(I+Nn/2+Nn/4)=Shuffle2(I)+3
4690      NEXT I
4700      MAT REORDER Y BY Shuffle2
4710      RAD
4720      FOR S=1 TO R
4730         L=2^(S-1)
4740         P=2^(R-S)
4750         Temp1=-P*2*PI*(1/Nn)
4760         FOR Q=0 TO L-1
4770            Ww(Q,1)=COS(Temp1*Q)
4780            Ww(Q,2)=SIN(Temp1*Q)
4790         NEXT Q
4800         FOR I=0 TO Nn-2*L STEP 2*L
4810            FOR Q=0 TO L-1
4820               J=I+Q
4830               Mm=J+L
4840               R1=Y(Mm)*Ww(Q,1)-Y2(Mm)*Ww(Q,2)
4850               R2=Y(Mm)*Ww(Q,2)+Y2(Mm)*Ww(Q,1)
4860               Y(Mm)=Y(J)-R1
4870               Y2(Mm)=Y2(J)-R2
4880               Y(J)=Y(J)+R1
4890               Y2(J)=Y2(J)+R2
4900            NEXT Q
4910         NEXT I
4920      NEXT S
4930 Fold_over:        !
4940      Inverse=2/Nn
4950      Amplitude=0
4960      FOR Q=0 TO (Nn/2)
4970         Ww(Q,1)=Inverse*SQR(Y(Q)^2+Y2(Q)^2)
4980         Amplitude=MAX(Amplitude,Ww(Q,1))
4990      NEXT Q
5000      Ww(0,1)=Ww(0,1)/2
5010      Ww(Nn/2,1)=Ww(Nn/2,1)/2
5020      Temp1=100/Amplitude
5030      FOR Q=0 TO Nn/2
```

```
5040        K(Q+Xmin+1,33)=INT(Ww(Q,1)*Temp1+.5)*Scale_factor(33)
5050     NEXT Q
5060     DISP " "
5070     BEEP
5080     DEG
5090     DEALLOCATE Ww(*)
5100     DEALLOCATE Shuffle2(*)
5110     DEALLOCATE Y(*)
5120     DEALLOCATE Y2(*)
5130     RETURN
5140  !
5150  ! ============================================================
5160  !    QUICK LOOK
5170  ! ============================================================
5180 Quick_look:    !
5190     GINIT
5200     GRAPHICS ON
5210     DEG
5220     LORG 5
5230     Xmin=0
5240     Xmax=MIN(7000,Nscans)
5250     Xmn=0
5260     Xmx=Xmax/1000
5270     I_ymin=1
5280     Power_ymin=1
5290     Ymin=-10
5300     I_ymax=1
5310     Power_ymax=1
5320     Ymax=10
5330     GOTO Plot_set_up
5340  !
5350  ! ============================================================
5360  !    SELECT CHANNEL
5370  ! ============================================================
5380 Select_channel:    !
5390     IF Split_flag=1 THEN
5400        First_flag=0
5410        Split_flag=0
5420        GOTO New_plot
5430     END IF
5440     INPUT "ENTER SIGNAL NUMBER TO BE PLOTTED: ",Channel_no
5450     IF Channel_no>28 AND Channel_no<33 THEN
5460        IF Channel_no MOD 2=0 THEN Channel_no=Channel_no-1
5470        GOTO Plot_position
5480     ELSE
5490        IF Channel_no=33 THEN
5500           GOTO Plot_fft
5510        ELSE
5520           IF Channel_no>18 THEN
5530              GOTO Plot_derived
5540           ELSE
5550              GOTO Plot_engg
5560           END IF
5570        END IF
5580     END IF
5590  !
5600  ! ============================================================
5610  !    NEW PLOT
5620  ! ============================================================
5630 New_plot:    !
5640     Split_flag=0
5650 New_plot_cont:!
5660     INPUT "ENTER SIGNAL NUMBER TO BE PLOTTED: ",Channel_no
5670     IF Channel_no<1 OR Channel_no>Total_channels THEN
5680        DISP "INVALID CHANNEL NUMBER TRY AGAIN ---";
5690        GOTO New_plot
```

```
5700      END IF
5710      IF Channel_no=33 THEN Fft_set_up
5720      IF Channel_no>18 THEN Input_x_range
5730 Input_x_range:     !
5740      IF Split_flag AND NOT First_flag THEN Input_y_range
5750      INPUT "ENTER XMIN, XMAX: ",Xmn,Xmx
5760      IF Xmn<0 OR Xmx<0 OR Xmn>Nscans/1000 OR Xmx>Nscans/1000 THEN
5770         DISP "X RANGE OUTSIDE OF LIMITS TRY AGAIN ---";
5780         GOTO Input_x_range
5790      END IF
5800      IF ABS(Xmn-Xmx)<.001 THEN
5810         DISP "TOTAL X-SPAN IS ZERO TRY AGAIN"
5820         WAIT 1
5830         GOTO Input_x_range
5840      END IF
5850 Input_y_range:     !
5860      IF Channel_no>28 AND Channel_no<33 THEN
5870         IF Channel_no=30 THEN Channel_no=29
5880         IF Channel_no=32 THEN Channel_no=31
5890         GOTO Position_set_up
5900      END IF
5910      INPUT "ENTER YMIN, YMAX: ",Ymin,Ymax
5920      PRINT CHR$(12)
5930      IF ABS(Ymin-Ymax)<.001 THEN
5940         PRINT "Y-RANGE <.001 TRY AGAIN"
5950         GOTO Input_y_range
5960      END IF
5970      !
5980 Nice_scale:     !TO CHOOSE RATIONAL Y SCALE
5990      IF Ymin=0 THEN
6000         Power_ymin=0
6010         Mult_ymin=0
6020         Power_ymax=INT(LGT(ABS(Ymax)))
6030         Mult_ymax=ABS(Ymax/10^Power_ymax)
6040         GOTO Next_part_0
6050      END IF
6060      IF Ymax=0 THEN
6070         Power_ymax=0
6080         Mult_ymax=0
6090         Power_ymin=INT(LGT(ABS(Ymin)))
6100         Mult_ymin=ABS(Ymin/10^Power_ymin)
6110         GOTO Next_part_0
6120      END IF
6130      Power_ymax=INT(LGT(ABS(Ymax)))
6140      Mult_ymax=ABS(Ymax/10^Power_ymax)
6150      Power_ymin=INT(LGT(ABS(Ymin)))
6160      Mult_ymin=ABS(Ymin/10^Power_ymin)
6170 Next_part_0:                !
6180      FOR I=0 TO 7
6190         IF Mult_ymin<=Vert_scale(I) THEN Next_part_1
6200      NEXT I
6210 Next_part_1:                !
6220      IF Ymin>0 THEN
6230         I_ymin=I-1
6240      ELSE
6250         I_ymin=I
6260      END IF
6270      FOR I=0 TO 7
6280         IF Mult_ymax<=Vert_scale(I) THEN Next_part_2
6290      NEXT I
6300 Next_part_2:                !
6310      IF Ymax<0 THEN
6320         I_ymax=I-1
6330      ELSE
6340         I_ymax=I
6350      END IF
```

```
6360     !
6370     Xmin=1000*Xmn
6380     Xmax=1000*Xmx
6390     !
6400     Ymin=Vert_scale(I_ymin)*10^Power_ymin*SGN(Ymin)
6410     Ymax=Vert_scale(I_ymax)*10^Power_ymax*SGN(Ymax)
6420     IF Ymin>0 AND Ymax>0 AND Ymin<.1*Ymax THEN
6430        Ymin=0
6440        GOTO Nice_scale
6450     END IF
6460     IF Ymin<0 AND Ymax>0 AND ABS(Ymin)<.1*Ymax THEN
6470        Ymin=-.1*Ymax
6480        GOTO Nice_scale
6490     END IF
6500     IF Ymin<0 AND Ymax<0 AND Ymax>.1*Ymin THEN
6510        Ymax=0
6520        GOTO Nice_scale
6530     END IF
6540     GOTO Plot_set_up
6550  !
6560  ! ============================================================
6570  !   TWO PLOT   SPLIT SCREEN ROUTINE
6580  ! ============================================================
6590  !
6600 Two_plot: !
6610     Split_size=2.5            !FOR USE IN "CSIZE Split_size"
6620     Split_flag=1
6630     Mask_word=1
6640     First_flag=NOT First_flag
6650     IF NOT First_flag THEN GSTORE Screen_buffer(*)
6660     GOTO New_plot_cont
6670  ! ============================================================
6680  !   FFT SET-UP
6690  ! ============================================================
6700 Fft_set_up:     !
6710     DEG
6720     CSIZE 3.5
6730     VIEWPORT 10,115,13,80
6740     Split_flag=0
6750     First_flag=0
6760     GCLEAR
6770     Max_frequency=200
6780     INPUT "ENTER MAXIMUM FREQUENCY TO BE PLOTTED: ",Max_frequency
6790     WINDOW 0,Max_frequency,0,100
6800     CLIP ON
6810     AXES Max_frequency/50,2,0,0,5,5
6820     CLIP OFF
6830     MOVE 0,-3
6840     LABEL "0"
6850     MOVE Max_frequency,-3
6860     LABEL VAL$(Max_frequency)
6870     MOVE Max_frequency/2,-5
6880     LABEL "FREQUENCY (hz)"
6890     MOVE Max_frequency/2,120
6900     LABEL Title$
6910     MOVE Max_frequency/2,115
6920     IF Fft_no>18 THEN
6930        LABEL "FFT of "&Calc_chanl_desc$(Fft_no)
6940        Multiplier=1/Scale_factor(Fft_no)
6950        Fft_units$=Units$(Fft_no)
6960     ELSE
6970        LABEL "FFT of "&Channel_desc$(Fft_no)
6980        Multiplier=Slope(Fft_no)
6990        Fft_units$="  volts"
7000        IF Fft_units THEN Fft_units$=Units$(Fft_no)
7010     END IF
```

```
7020     MOVE Max_frequency/2,110
7030     LABEL USING "21A,D.DDE,7A";"MAXIMUM AMPLITUDE =  ",Amplitude*Multiplier
,Fft_units$
7040     MOVE Max_frequency/2,105
7050     LABEL USING "DDDD,25A,D.DD,2A";Nn," POINTS STARTING AT TIME ",Fft_min/1
000," s"
7060     LDIR 90
7070     MOVE -.05*Max_frequency,50
7080     LABEL "RELATIVE AMPLITUDE"
7090     MOVE -.03*Max_frequency,0
7100     LABEL "0%"
7110     MOVE -.03*Max_frequency,100
7120     LABEL "100%"
7130     CLIP ON
7140     LDIR 0
7150     GOTO Plot_fft
7160  !
7170  ! ============================================================
7180  !   POSITION SET-UP
7190  ! ============================================================
7200 Position_set_up:    !
7210     DEG
7220     GCLEAR
7230     Split_flag=0
7240     First_flag=0
7250     CSIZE 3.5
7260     VIEWPORT 10,115,13,90
7270     CLIP ON
7280     SHOW -1.0,1.0,-1.0,1.0
7290     AXES .02,.02,0,0,5,5
7300     MOVE SIN(0)*.7,COS(0)*.7
7310     FOR Angle=0 TO 360 STEP 3
7320        DRAW SIN(Angle)*.7,COS(Angle)*.7
7330     NEXT Angle
7340     LORG 4
7350     MOVE 1.0,0
7360     LABEL "STARBOARD"
7370     LORG 3
7380     MOVE .7,0
7390     LABEL "0.7 mm"
7400     LORG 1
7410     MOVE 0,.7
7420     LABEL "0.7 mm"
7430     LORG 4
7440     MOVE -1.0,0
7450     LABEL "PORT"
7460     LORG 5
7470     MOVE .7,.9
7480     IF Channel_no=31 THEN LABEL "FORWARD PROBE LOCATION"
7490     IF Channel_no=29 THEN LABEL "AFT PROBE LOCATION"
7500     IF NOT Position_flag THEN GOSUB Rotation_calc
7510     GOTO Plot_position
7520  !
7530  ! ============================================================
7540  !   PLOT SET-UP
7550  ! ============================================================
7560 Plot_set_up:    !
7570     GCLEAR
7580     IF Split_flag AND NOT First_flag THEN GLOAD Screen_buffer(*)
7590     CLIP ON
7600     Ymin=Vert_scale(I_ymin)*10^Power_ymin*SGN(Ymin)
7610     Ymax=Vert_scale(I_ymax)*10^Power_ymax*SGN(Ymax)
7620     IF Ymin=Ymax THEN
7630        DISP "YMIN=YMAX  SELECT ""VIEW"" AND TRY AGAIN"
7640        BEEP
7650        GOTO Main_loop
```

```
7660    END IF
7670    Ymin$=VAL$(Ymin)
7680    Ymax$=VAL$(Ymax)
7690    CSIZE 3.5
7700    VIEWPORT 15,130,13,90
7710    IF Split_flag THEN CSIZE (Split_size)
7720    IF Split_flag AND First_flag THEN VIEWPORT 15,130,52,90
7730    IF Split_flag AND NOT First_flag THEN VIEWPORT 15,130,11,49
7740    FRAME
7750    WINDOW Xmin,Xmax,Ymin,Ymax
7760    X_scale=Xmax-Xmin
7770    Y_scale=Ymax-Ymin
7780    X_tick=100
7790    X_major=5
7800    IF X_scale<=1000 THEN
7810       X_tick=50
7820       X_major=4
7830    END IF
7840    IF X_scale<=500 THEN
7850       X_tick=25
7860       X_major=4
7870    END IF
7880    IF X_scale<=100 THEN
7890       X_tick=10
7900       X_major=5
7910    END IF
7920    Yminor=20
7930    IF Y_scale<500.1 THEN Yminor=10
7940    IF Y_scale<100.1 THEN Yminor=2
7950    IF Y_scale<50.05 THEN Yminor=1
7960    IF Y_scale<10.005 THEN Yminor=.2
7970    IF Y_scale<5.005 THEN Yminor=.1
7980    IF Y_scale<1.005 THEN Yminor=.02
7990    IF Y_scale<.5005 THEN Yminor=.01
8000    AXES X_tick,Yminor,Xmin,Ymin,X_major,5,3
8010    MOVE Xmin,0
8020    DISABLE
8030    LINE TYPE 3
8040    DRAW Xmax,0
8050    LINE TYPE 1
8060    ENABLE
8070    CLIP OFF
8080    LDIR 0
8090    MOVE Xmin+X_scale/2,Ymax+.05*Y_scale
8100    IF Split_flag AND First_flag THEN LABEL "ANALYSIS DATE: "&Today$&"     T
IME: "&Time_today$
8110    Label_increment=X_tick*X_major*2
8120    IF X_scale<=1000 THEN Label_increment=X_tick*X_major
8130    FOR I=Xmin TO Xmax STEP Label_increment
8140       MOVE I,Ymin-.05*Y_scale
8150       LABEL I/1000
8160    NEXT I
8170    MOVE Xmin+.5*X_scale,Ymin-.10*Y_scale
8180    IF Split_flag AND Not_first_flag THEN LABEL "TIME (seconds)"
8190    IF NOT Split_flag THEN LABEL "TIME (seconds)"
8200    MOVE Xmin-.05*X_scale,0
8210    IF Ymin<0 AND Ymax>0 THEN LABEL "0"
8220    MOVE Xmin-.05*X_scale,Ymin
8230    LABEL Ymin$
8240    MOVE Xmin-.05*X_scale,Ymax
8250    LABEL Ymax$
8260    LDIR 90
8270    MOVE Xmin-.09*X_scale,Ymin+.5*Y_scale
8280    IF (Channel_no<=18) OR ((Channel_no=35) AND (Filter_channel<=18)) THEN
8290       LABEL Channel_desc$(Filter_channel)&Units$(Filter_channel)
8300    ELSE
```

```
8310        LABEL Calc_chanl_desc$(Filter_channel)&Units$(Filter_channel)
8320     END IF
8330     LDIR 0
8340     MOVE Xmin+.5*X_scale,Ymin+.95*Y_scale
8350     LABEL Title$
8360     MOVE Xmin+.5*X_scale,Ymin+.90*Y_scale
8370     LABEL Dates$&"   "&Times$
8380     CLIP ON
8390     CSIZE 3.5
8400     IF (Channel_no<=18) OR ((Channel_no=35) AND (Filter_channel<=18)) THEN
8410        GOTO Plot_engg
8420     ELSE
8430        GOTO Plot_derived
8440     END IF
8450  !
8460  ! ==============================================================
8470  !   PLOT ENGG UNITS
8480  ! ==============================================================
8490 Plot_engg:     !
8500     PEN 1
8510     MOVE Xmin,Signals(Xmin+1,Channel_no)*Slope(Channel_no)+Offset(Channel_n
o)
8520     Step_size=MAX(1,INT(X_scale/1200))
8530     FOR I=MAX(1,INT((Xmin+1)/Corr_factor)) TO MIN(INT(Xmax/Corr_factor),Nsc
ans) STEP Step_size
8540        DRAW I*Corr_factor,Signals(I,Channel_no)*Slope(Channel_no)+Offset(Ch
annel_no)
8550     NEXT I
8560     MOVE (Xmin+1),Signals(Xmin+1,Channel_no)*Slope(Channel_no)+Offset(Chann
el_no)
8570     PEN 0
8580     LABEL "+"
8590     PEN 1
8600     Current_record=Xmin+1
8610     GOTO Main_loop
8620  !
8630  ! ==============================================================
8640  !   PLOT DERIVED FORCES
8650  ! ==============================================================
8660 Plot_derived:     !
8670     PEN 1
8680     MOVE Xmin,K(Xmin+1,Channel_no)/Scale_factor(Channel_no)
8690     Step_size=MAX(1,INT(X_scale/1200))
8700     FOR I=MAX(1,INT((Xmin+1)/Corr_factor)) TO MIN(INT(Xmax/Corr_factor),Nsc
ans) STEP Step_size
8710        DRAW I*Corr_factor,K(I,Channel_no)/Scale_factor(Channel_no)
8720     NEXT I
8730     MOVE (Xmin+1),K(Xmin+1,Channel_no)/Scale_factor(Channel_no)
8740     PEN 0
8750     LABEL "+"
8760     PEN 1
8770     Current_record=Xmin+1
8780     GOTO Main_loop
8790  !
8800  ! ==============================================================
8810  !   PLOT POSITION
8820  ! ==============================================================
8830 Plot_position:     !
8840     Wait_time=0
8850     INPUT "ENTER WAIT TIME BETWEEN PLOT UPDATES (seconds)",Wait_time
8860     PEN 1
8870     MOVE K(Xmin+1,Channel_no)/Scale_factor(Channel_no),K(Xmin+1,Channel_no+
1)/Scale_factor(Channel_no)
8880     Step_size=MAX(1,INT(X_scale/1200))
8890     FOR I=Xmin+1 TO Xmax STEP Step_size
8900        DRAW K(I,Channel_no)/Scale_factor(Channel_no),K(I,Channel_no+1)/Scal
```

```
e_factor(Channel_no)
          WAIT Wait_time
8910      NEXT I
8920      MOVE K(Xmin+1,Channel_no)/Scale_factor(Channel_no),K(Xmin+1,Channel_no+
8930
1)/Scale_factor(Channel_no)
          PEN 0
8940      LABEL "+"
8950      PEN 1
8960      Current_record=Xmin+1
8970      GOTO Main_loop
8980
8990   !
9000   ! ================================================================
9010   !    PLOT FFT
9020   ! ================================================================
9030 Plot_fft:      !
         PEN 1
9040     MOVE 0,K(Fft_min+1,33)/Scale_factor(33)
9050     FOR I=Fft_min+1 TO Fft_min+1+INT(.5+(Max_frequency*Nn)/(Scan_rate))
9060        DRAW (I-Fft_min-1)*(Scan_rate/Nn),K(I,33)/Scale_factor(33)
9070     NEXT I
9080     GOTO Main_loop
9090
9100   !
9110   ! ================================================================
9120   !    LABEL UP
9130   ! ================================================================
9140 Label_up:      !
         IF Channel_no>28 AND Channel_no<34 THEN RETURN
9150     LORG 2
9160     LDIR 90
9170     Space1$="-"
9180     Space2$=" "
9190     GOSUB Label_this
9200     LDIR 0
9210     LORG 5
9220     RETURN
9230
9240   !
9250   ! ================================================================
9260   !    LABEL THIS
9270   ! ================================================================
9280 Label_this:     !
         IF Split_flag THEN CSIZE (Split_size)
9290     IF Channel_no>18 THEN
9300       MOVE Current_record*Corr_factor,K(Current_record,Channel_no)/Scale_f
9310       IF Channel_no>18 THEN
actor(Channel_no)
           String=INT(LGT(ABS(K(Current_record,Channel_no)/Scale_factor(Channel
9320
_no))))
           IF String=3 THEN LABEL USING "A,MDDDD,A";Space1$,(K(Current_record,Ch
9330
hannel_no)/Scale_factor(Channel_no)),Space2$
           IF String=2 THEN LABEL USING "A,MDDD,A";Space1$,(K(Current_record,C
9340
annel_no)/Scale_factor(Channel_no)),Space2$
           IF String=1 THEN LABEL USING "A,MDD.D,A";Space1$,(K(Current_record,C
9350
hannel_no)/Scale_factor(Channel_no)),Space2$
           IF String=0 THEN LABEL USING "A,MD.DD,A";Space1$,(K(Current_record,C
9360
hannel_no)/Scale_factor(Channel_no)),Space2$
           IF String<=-1 THEN LABEL USING "A,M.DDD,A";Space1$,(K(Current_record
9370
,Channel_no)/Scale_factor(Channel_no)),Space2$
         ELSE
9380       IF Units THEN
9390         MOVE Current_record*Corr_factor,Signals(Current_record,Channel_no
9400
)*Slope(Channel_no)+Offset(Channel_no)
             String=INT(LGT(ABS(Signals(Current_record,Channel_no)*Slope(Chann
9410
el_no)+Offset(Channel_no))))
             IF String=3 THEN LABEL USING "A,MDDDD,A";Space1$,(Signals(Current
9420
_record,Channel_no)*Slope(Channel_no)+Offset(Channel_no)),Space2$
             IF String=2 THEN LABEL USING "A,MDDD,A";Space1$,(Signals(Current_
9430
record,Channel_no)*Slope(Channel_no)+Offset(Channel_no)),Space2$
```

TITLE: "ANALYZE"

APPENDIX G

**CANADIAN MARINE DRILLING LIMITED**

MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

```
9440           IF String=1 THEN LABEL USING "A,MDD.D,A";Space1$,(Signals(Current
_record,Channel_no)*Slope(Channel_no)+Offset(Channel_no)),Space2$
9450           IF String=0 THEN LABEL USING "A,MD.DD,A";Space1$,(Signals(Current
_record,Channel_no)*Slope(Channel_no)+Offset(Channel_no)),Space2$
9460           IF String<=-1 THEN LABEL USING "A,M.DDD,A";Space1$,(Signals(Curre
nt_record,Channel_no)*Slope(Channel_no)+Offset(Channel_no)),Space2$
9470        ELSE
9480           MOVE Current_record*Corr_factor,Signals(Current_record,Channel_no
)*.005
9490           String=INT(LGT(ABS(Signals(Current_record,Channel_no)*.005)))
9500           IF String=3 THEN LABEL USING "A,MDDDD,A";Space1$,(Signals(Current
_record,Channel_no)*.005),Space2$
9510           IF String=2 THEN LABEL USING "A,MDDD,A";Space1$,(Signals(Current_
record,Channel_no)*.005),Space2$
9520           IF String=1 THEN LABEL USING "A,MDD.D,A";Space1$,(Signals(Current
_record,Channel_no)*.005),Space2$
9530           IF String=0 THEN LABEL USING "A,MD.DD,A";Space1$,(Signals(Current
_record,Channel_no)*.005),Space2$
9540           IF String<=-1 THEN LABEL USING "A,M.DDD,A";Space1$,(Signals(Curre
nt_record,Channel_no)*.005),Space2$
9550        END IF
9560     END IF
9570     CSIZE 3.5
9580     RETURN
9590  !
9600  ! ==========================================================
9610  !    LABEL DOWN
9620  ! ==========================================================
9630 Label_down:   !
9640     IF Channel_no>28 AND Channel_no<34 THEN RETURN
9650     LORG 8
9660     LDIR 90
9670     Space1$=" "
9680     Space2$="-"
9690     GOSUB Label_this
9700     LDIR 0
9710     LORG 5
9720     RETURN
9730  !
9740  ! ==========================================================
9750  !    ROTATION CALCULATE
9760  ! ==========================================================
9770 Rotation_calc:    !
9780     DEG
9790     Cose1=COS(E1)*Scale_factor(29)*Slope(11)
9800     Sine1=SIN(E1)*Scale_factor(29)*Slope(11)
9810     Cose2=COS(E2)*Scale_factor(29)*Slope(11)
9820     Sine2=SIN(E2)*Scale_factor(29)*Slope(11)
9830     DISP "CALCULATING THE POSITION OF THE SHAFT"
9840     FOR I=1 TO 7000
9850        K(I,29)=INT(Cose1*Signals(I,12)-Sine1*Signals(I,11)+.5)
9860        K(I,30)=INT(Sine1*Signals(I,12)+Cose1*Signals(I,11)+.5)
9870        K(I,31)=INT(Cose2*Signals(I,13)-Sine2*Signals(I,14)+.5)
9880        K(I,32)=INT(Sine2*Signals(I,13)+Cose2*Signals(I,14)+.5)
9890     NEXT I
9900     DISP " "
9910     Position_flag=1
9920     RETURN
9930  !
9940  ! ==========================================================
9950  !    CALCULATE THE FORCES FROM THE 'G' MATRIX, WITH OPTIONALLY
9960  !      HYDRO-DYNAMIC OFFSET SUBTRACTED.
9970  ! ==========================================================
9980 Calculate:    !
9990     Calculate_flag=1           !USED TO GET RID OF DISP IN MOVE_CURSOR
10000    X_start=MAX(0,Xmin-150)
```

```
10010     X_finish=MIN(Nscans,Xmax+150)
10020     REDIM G(6,X_start+1:X_finish)
10030     ALLOCATE REAL Fred(1:18,1:7000)
10040     ALLOCATE REAL F(19:21,X_start+1:X_finish)
10050     MAT G= (0)
10060     Y$=""
10070     INPUT "WOULD YOU LIKE TO SUBTRACT THE HYDRO-DYNAMIC EFFECT? (Y or N)",Y
$
10080     IF Y$[1,1]="Y" OR Y$[1,1]="y" THEN
10090        IF Channel_no>6 THEN
10100           DISP "YOU MUST VIEW CHANNEL 1 TO 6 TO SUBTRACT HYDRODYNAMIC PART
OF SIGNAL"
10110           BEEP
10120           RETURN
10130        END IF
10140        GOSUB Hydrodynamic
10150     ELSE
10160        DISP "SHUFFLING DATA"
10170        IF Xmin=0 AND Xmax=Nscans THEN
10180           MAT Fred= TRN(Signals)
10190           REDIM Fred(1:6,1:7000)
10200        ELSE
10210           REDIM Fred(1:6,1:7000)
10220           FOR I=Xmin+1 TO Xmax
10230              FOR J=1 TO 6
10240                 Fred(J,I)=Signals(I,J)
10250              NEXT J
10260           NEXT I
10270        END IF
10280     END IF
10290     Loc=1
10300     PRINT RPT$(CHR$(10),35)
10310     PRINT "MATRIX 1  :ALL 6 CHANNELS ,ALL LOCATIONS"
10320     PRINT "MATRIX 2  :CHANNEL 6 DEAD, ALL LOCATIONS"
10330     PRINT "MATRIX 3  :CHANNEL 4 DEAD, ALL LOCATIONS"
10340     PRINT "MATRIX 4  :"
10350     PRINT "MATRIX 5  :"
10360     PRINT "MATRIX 6  :"
10370     INPUT "ENTER WHICH 'A' MATRIX YOU WOULD LIKE TO USE (1-6)",Loc
10380     PRINT CHR$(12)
10390     FOR I=1 TO 3
10400        FOR J=1 TO 6
10410           A(I,J)=A_matrix(Loc,I,J)
10420        NEXT J
10430     NEXT I
10440     DISP "CALCULATING FORCES"
10450     MAT F= A*Fred
10460     FOR I=X_start+1 TO X_finish
10470        K(I,19)=INT(F(19,I)*Scale_factor(19)+.5)      ! BENDING MOMENT
10480        K(I,20)=INT(F(20,I)*Scale_factor(20)+.5)      ! SPINDLE TORQUE
10490        K(I,21)=INT(F(21,I)*Scale_factor(21)+.5)      ! FORCE
10500        IF F(21,I)=0 THEN Next_point
10510        Temp_pos=(F(19,I)/F(21,I)*Scale_factor(22)+.5) ! HEIGHT ABOVE BLADE
FOOT IN M
10520        IF ABS(Temp_pos)<32677 THEN K(I,22)=INT(Temp_pos)
10530        Temp_pos=-1*(F(20,I)/F(21,I)*Scale_factor(23)+.5) ! DISTANCE FROM CE
NTERLINE IN M (-ve SIGN TO TAKE INTO ACCOUNT OF SENSE OF TORQUE)
10540        IF ABS(Temp_pos)<32677 THEN K(I,23)=INT(Temp_pos)
10550 Next_point:          !
10560     NEXT I
10570     DISP "FINISHED CALCULATING FORCES"
10580     BEEP
10590     Calculate_flag=0
10600     DEALLOCATE F(*)
10610     DEALLOCATE Fred(*)
10620     RETURN
```

```
10630 !
10640 ! ========================================================
10650 !   HYDRODYNAMIC CORRECTION
10660 ! ========================================================
10670 Hydrodynamic:   !
10680     OFF KEY
10690     ON KEY 0 LABEL "SELECT POINT",3 GOSUB Get_point
10700     ON KEY 1 LABEL " ",3 GOSUB Idle
10710     ON KEY 2 LABEL " ",3 GOSUB Idle
10720     ON KEY 3 LABEL " ",3 GOSUB Idle
10730     ON KEY 4 LABEL " ",3 GOSUB Idle
10740     ON KEY 5 LABEL " ",3 GOSUB Idle
10750     ON KEY 6 LABEL " ",3 GOSUB Idle
10760     ON KEY 7 LABEL " ",3 GOSUB Idle
10770     ON KEY 8 LABEL " ",3 GOSUB Idle
10780     ON KEY 9 LABEL "EXIT",3 GOSUB Hydro_exit
10790     Xa=0
10800     Xb=0
10810     X1=0
10820     X2=0
10830     First_time=1
10840     Hydro_exit=0
10850     BEEP
10860 Hydro_loop:      !
10870     DISP "SELECT KEY FOR HYDRO-DYNAMIC CORRECTION "
10880     DISABLE
10890     IF Xa<>0 THEN GOSUB Mean_calculate
10900     ENABLE
10910     IF NOT Hydro_exit THEN Hydro_loop
10920     DISABLE
10930     GOSUB Hydro_calculate
10940     ENABLE
10950     GOSUB Main_keys
10960     RETURN
10970 !
10980 ! ========================================================
10990 !   IDLE
11000 ! ========================================================
11010 Idle:RETURN
11020 !
11030 ! ========================================================
11040 !   HYDRO EXIT
11050 ! ========================================================
11060 Hydro_exit:   !
11070     IF NOT First_time AND Xb=0 THEN Hydro_exit=1
11080     IF NOT Hydro_exit THEN BEEP
11090     RETURN
11100 !
11110 ! ========================================================
11120 !   GET POINT
11130 ! ========================================================
11140 Get_point:   !
11150     Xa=Xb
11160     Xb=Current_record
11170     MOVE Current_record*Corr_factor,Signals(Current_record,Channel_no)*.005
-.05*Y_scale
11180     IF Xa=0 THEN LABEL CHR$(91)
11190     IF Xa<>0 THEN LABEL CHR$(93)
11200     RETURN
11210 !
11220 ! ========================================================
11230 !   MEAN CALCULATE
11240 ! ========================================================
11250 Mean_calculate:   !
11260     DISP "CALCULATING MEAN HYDRO-DYNAMIC OFFSET"
11270     FOR J=1 TO 6
```

```
11280       Total=0
11290       FOR I=Xa TO Xb
11300          Total=Total+Signals(I,J)
11310       NEXT I
11320       Mean(1,J)=Mean(2,J)
11330       Mean(2,J)=Total/(Xb-Xa+1)
11340    NEXT J
11350    X1=X2
11360    X2=INT((Xa+Xb)/2)
11370    Xa=0
11380    Xb=0
11390    IF X1<>0 THEN GOSUB Hydro_calculate
11400    RETURN
11410 !
11420 ! ============================================================
11430 !   HYDRO CALCULATE
11440 ! ============================================================
11450 Hydro_calculate:    !
11460    DISP "CALCULATING HYDRO-DYNAMIC OFFSETS"
11470    Start=X1
11480    Finish=X2
11490    IF First_time THEN Start=X_start
11500    IF Hydro_exit THEN Finish=X_finish
11510    IF Hydro_exit THEN Start=X2
11520    FOR J=1 TO 6
11530       Mean_slope=(Mean(2,J)-Mean(1,J))/(X2-X1)
11540       FOR I=Start+1 TO Finish
11550          G(J,I)=Signals(I,J)-(I-X1)*Mean_slope-Signals(X1,J)
11560       NEXT I
11570    NEXT J
11580    First_time=0
11590    RETURN
11600 !
11610 ! ============================================================
11620 !   READ DATA
11630 ! ============================================================
11640 Read_data:    !
11650    File$="PROPDATA"
11660    INPUT "IF NAME OF DATA FILE IS""PROPDATA"" CONTINUE ELSE INPUT FILE NAM
E: ",File$
11670    ASSIGN @Data_file TO File$
11680    IF File$<>"PROPDATA" THEN
11690       ENTER @Data_file;Title$,Dates$,Times$,N_channels,Nscans,Scan_rate,Si
gnals(*)
11700    ELSE
11710       ENTER @Data_file;Title$,Dates$,Times$,N_channels,Nscans,Scan_rate,In
t_data,Int_pointer,Signals(*)
11720    END IF
11730    ASSIGN @Data_file TO *
11740    IF File$<>"PROPDATA" THEN Channel_desc$(13)="FWD PORT PROBE"
11750    IF Signals(1,1)<-2049 THEN GOSUB Data_convert
11760    Title$=TRIM$(Title$)
11770    Corr_factor=1000/Scan_rate
11780    RETURN
11790 !
11800 ! ============================================================
11810 !   READ MAGNETIC TAPE
11820 ! ============================================================
11830 Read_mag_tape:    !
11840    !
11850    IF First_tape_read THEN
11860       INPUT "IS THE IDT TAPE DRIVE ON-LINE, 1600 BPI?",R$
11870       OUTPUT 716;"BS(4000)"
11880       First_tape_read=0
11890    END IF
11900    Space_ahead=1
```

```
11910 Read_more_tape:       !
11920    OUTPUT 716;"MF("&VAL$(Space_ahead)&")"
11930    DISP "SEARCHING FOR DISC: ";Disc_requested
11940    ASSIGN @Device TO 717
11950    CONTROL @Device,3;1,0,1
11960    ENTER @Device USING "80A,12A,12A";Title$,Dates$,Times$
11970    IF Title$[1,1]=CHR$(10) THEN End_of_data=1
11980    IF End_of_data THEN RETURN
11990    ENTER @Device;Disc_number,N_channels,Nscans,Scan_rate,Int_data,Int_poin
ter
12000    Space_ahead=Disc_requested-Disc_number
12010    IF Space_ahead<>0 THEN Read_more_tape
12020    OUTPUT 716;"MB(0)"
12030    TRANSFER @Device TO @Bufin;RECORDS 63,EOR (COUNT 4000,END),WAIT
12040    ASSIGN @Device TO *
12050    Title$=TRIM$(Title$)
12060    Corr_factor=1000/Scan_rate
12070    RETURN
12080 !
12090 ! ================================================================
12100 !    RPM CALCULATE
12110 ! ================================================================
12120 Rpm_calculate:      !
12130    DISP "CALCULATING RPM FROM SHAFT RATE PULSES"
12140    Rpm_ref=150            !REFERENCE LEVEL IN A/D COUNTS
12150    FOR I=1 TO 7000
12160       IF Signals(I,Rpm_channel)<-Rpm_ref THEN First_found
12170    NEXT I
12180    DISP "NO RPM PULSES FOUND"
12190    WAIT 1
12200    BEEP
12210    RETURN
12220    !
12230 First_found:       !
12240    IF I>1 THEN
12250       Rpm_pulse(0)=1
12260       Rpm_pulse(1)=I
12270    ELSE
12280       Rpm_pulse(0)=0
12290       Rpm_pulse(1)=1
12300    END IF
12310    !
12320 Pulse_loop:    !
12330    FOR J=2 TO 50
12340       FOR I=Rpm_pulse(J-1)+240 TO Rpm_pulse(J-1)+400
12350          IF I>7000 THEN Last_pulse
12360          IF Signals(I,Rpm_channel)<-Rpm_ref THEN Pulse_found
12370       NEXT I
12380 Pulse_found:          !
12390       Rpm_pulse(J)=I
12400    NEXT J
12410 Last_pulse:       !
12420    Numb_of_pulse=J
12430    Rpm_pulse(J)=7000
12440    FOR J=2 TO Numb_of_pulse-1
12450       Rpm(J)=INT(60*Scale_factor(34)/((Rpm_pulse(J)-Rpm_pulse(J-1))/Scan_r
ate)+.5)
12460    NEXT J
12470    !
12480    !TRANSFFERING SHAFT SPEED DATA INTO K-ARRAY
12490    !
12500    Rpm(1)=Rpm(2)
12510    FOR J=1 TO Numb_of_pulse
12520       FOR I=Rpm_pulse(J) TO Rpm_pulse(J+1)-1
12530          K(I,34)=Rpm(J)
12540       NEXT I
```

```
12550    NEXT J
12560    FOR I=1 TO Rpm_pulse(1)
12570       K(I,34)=Rpm(2)
12580    NEXT I
12590    DISP ""
12600    RETURN
12610 !
12620 ! ============================================================
12630 !   GET SPEED
12640 ! ============================================================
12650 Get_speed:    !
12660    FOR J=1 TO Numb_of_pulse
12670       IF Current_record<Rpm_pulse(J) THEN Speed_found
12680    NEXT J
12690 Speed_found:       !
12700    Shaft_speed=Rpm(J)
12710    RETURN
12720 !
12730 ! ============================================================
12740 !   DIGITAL FILTER
12750 ! ============================================================
12760 Digital_filter:    !
12770    INPUT "FILTER FORCES OR CHANNEL DATA? F or C",R$
12780    IF UPC$(R$[1,1])="C" THEN GOTO Signal_filter
12790    IF NOT Filter_flag THEN GOSUB Filter_design
12800    ALLOCATE REAL Filter_temp(1:2000,19:21)
12810    !
12820    !   PRE FILTER
12830    !
12840    DISP "PERFORMING PRE-FILTERING OF DATA"
12850    Total_size=Pre_size*2+1
12860    ALLOCATE INTEGER B(1:Total_size)
12870    FOR I=1 TO Total_size-4
12880       B(I)=I+4
12890    NEXT I
12900    FOR I=1 TO 4
12910       B(I+Total_size-4)=I
12920    NEXT I
12930    ALLOCATE REAL H1(1:Total_size)
12940    ALLOCATE REAL H2(1:Total_size)
12950    ALLOCATE REAL H3(1:Total_size)
12960    FOR I=1 TO Total_size
12970       Time_index=Xmin+1-Pre_size+I-1-4*(Post_size)
12980       IF (Time_index<=0) OR (Time_index>Nscans) THEN
12990          H1(I)=0
13000          H2(I)=0
13010          H3(I)=0
13020       ELSE
13030          H1(I)=K(Time_index,19)
13040          H2(I)=K(Time_index,20)
13050          H3(I)=K(Time_index,21)
13060       END IF
13070    NEXT I
13080    L=0
13090    FOR I=Xmin+1-4*Post_size TO Xmax+4*Post_size STEP 4
13100       L=L+1
13110       MAT F1= Pre_filter*H1
13120       MAT F2= Pre_filter*H2
13130       MAT F3= Pre_filter*H3
13140       Filter_temp(L,19)=F1(1)
13150       Filter_temp(L,20)=F2(1)
13160       Filter_temp(L,21)=F3(1)
13170       MAT REORDER H1 BY B
13180       MAT REORDER H2 BY B
13190       MAT REORDER H3 BY B
13200       FOR J=1 TO 4
```

```
13210         IF ((I+J)<=0) OR ((I+J)>Nscans) THEN
13220            H1(Total_size-4+J)=0
13230            H2(Total_size-4+J)=0
13240            H3(Total_size-4+J)=0
13250         ELSE
13260            H1(Total_size-4+J)=K(I+J+Pre_size,19)
13270            H2(Total_size-4+J)=K(I+J+Pre_size,20)
13280            H3(Total_size-4+J)=K(I+J+Pre_size,21)
13290         END IF
13300      NEXT J
13310   NEXT I
13320   DEALLOCATE B(*)
13330   DEALLOCATE H1(*)
13340   DEALLOCATE H2(*)
13350   DEALLOCATE H3(*)
13360   !
13370   !     POST FILTER
13380   !
13390   DISP "PERFORMING POST-FILTERING OF DATA"
13400   Total_size=Post_size*2+1
13410   ALLOCATE INTEGER B(1:Total_size)
13420   FOR I=1 TO Total_size-1
13430      B(I)=I+1
13440   NEXT I
13450   B(Total_size)=1
13460   ALLOCATE REAL H1(1:Total_size)
13470   ALLOCATE REAL H2(1:Total_size)
13480   ALLOCATE REAL H3(1:Total_size)
13490   FOR I=1 TO Total_size
13500      H1(I)=Filter_temp(I,19)
13510      H2(I)=Filter_temp(I,20)
13520      H3(I)=Filter_temp(I,21)
13530   NEXT I
13540   L=0
13550   FOR I=Xmin+1 TO Xmax STEP 4
13560      L=L+1
13570      MAT F1= Post_filter*H1
13580      MAT F2= Post_filter*H2
13590      MAT F3= Post_filter*H3
13600      K(I,24)=INT(F1(1)+.5)
13610      K(I,25)=INT(F2(1)+.5)
13620      K(I,26)=INT(F3(1)+.5)
13630      Temp_pos=(F1(1)/F3(1)*Scale_factor(27)+.5)
13640      IF ABS(Temp_pos)<32677 THEN K(I,27)=INT(Temp_pos)
13650      Temp_pos=(F2(1)/F3(1)*Scale_factor(28)+.5)
13660      IF ABS(Temp_pos)<32677 THEN K(I,28)=INT(Temp_pos)
13670      MAT REORDER H1 BY B
13680      MAT REORDER H2 BY B
13690      MAT REORDER H3 BY B
13700      H1(Total_size)=Filter_temp(L+Total_size,19)
13710      H2(Total_size)=Filter_temp(L+Total_size,20)
13720      H3(Total_size)=Filter_temp(L+Total_size,21)
13730   NEXT I
13740   FOR I=Xmin+1 TO Xmax-4 STEP 4
13750      FOR J=1 TO 3
13760         FOR L=24 TO 28
13770            Temp_pos=((K(I+4,L)*1.0-K(I,L))*J*.25+K(I,L)+.5)
13780            IF ABS(Temp_pos)<32677 THEN K(I+J,L)=INT(Temp_pos)
13790         NEXT L
13800      NEXT J
13810   NEXT I
13820   DISP "FILTERING DONE"
13830   DEALLOCATE B(*)
13840   DEALLOCATE Filter_temp(*)
13850   DEALLOCATE H1(*)
13860   DEALLOCATE H2(*)
```

```
13870    DEALLOCATE H3(*)
13880    RETURN
13890 !
13900 ! ===============================================================
13910 !   SIGNAL FILTER  -  DIGITALLY FILTER ANY CHANNEL
13920 ! ===============================================================
13930 Signal_filter:   !
13940    IF NOT Filter_flag THEN GOSUB Filter_design
13950    ALLOCATE REAL Filter_temp_2(1:7000)
13960    !
13970    !   PRE FILTER
13980    !
13990    DISP "PERFORMING PRE-FILTERING OF DATA"
14000    Total_size=Pre_size*2+1
14010    ALLOCATE INTEGER B(1:Total_size)
14020    FOR I=1 TO Total_size-4
14030       B(I)=I+4
14040    NEXT I
14050    FOR I=1 TO 4
14060       B(I+Total_size-4)=I
14070    NEXT I
14080    ALLOCATE REAL H1(1:Total_size)
14090    FOR I=1 TO Total_size
14100       Time_index=Xmin+1-Pre_size+I-1-4*(Post_size)
14110       IF (Time_index<=0) OR (Time_index>Nscans) THEN
14120          H1(I)=0
14130       ELSE
14140           IF Channel_no>18 THEN H1(I)=K(Time_index,Channel_no)
14150           IF Channel_no<19 THEN H1(I)=Signals(Time_index,Channel_no)
14160       END IF
14170    NEXT I
14180    L=0
14190    FOR I=Xmin+1-4*Post_size TO Xmax+4*Post_size STEP 4
14200       L=L+1
14210       MAT F1= Pre_filter*H1
14220       Filter_temp_2(L)=F1(1)
14230       MAT REORDER H1 BY B
14240       FOR J=1 TO 4
14250          IF ((I+J)<=0) OR ((I+J)>Nscans) THEN
14260             H1(Total_size-4+J)=0
14270          ELSE
14280             H1(Total_size-4+J)=K(I+J+Pre_size,Channel_no)
14290          END IF
14300       NEXT J
14310    NEXT I
14320    DEALLOCATE B(*)
14330    DEALLOCATE H1(*)
14340    !
14350    !     POST FILTER
14360    !
14370    DISP "PERFORMING POST-FILTERING OF DATA"
14380    Total_size=Post_size*2+1
14390    ALLOCATE INTEGER B(1:Total_size)
14400    FOR I=1 TO Total_size-1
14410       B(I)=I+1
14420    NEXT I
14430    B(Total_size)=1
14440    ALLOCATE REAL H1(1:Total_size)
14450    FOR I=1 TO Total_size
14460       H1(I)=Filter_temp_2(I)
14470    NEXT I
14480    L=0
14490    FOR I=Xmin+1 TO Xmax STEP 4
14500       L=L+1
14510       MAT F1= Post_filter*H1
14520       K(I,35)=INT(F1(1)+.5)
```

```
14530       MAT REORDER H1 BY B
14540       H1(Total_size)=Filter_temp_2(L+Total_size)
14550    NEXT I
14560    FOR I=Xmin+1 TO Xmax-4 STEP 4
14570       FOR J=1 TO 3
14580             Temp_pos=((K(I+4,35)*1.0-K(I,35))*J*.25+K(I,35)+.5)
14590             IF ABS(Temp_pos)<32677 THEN K(I+J,35)=INT(Temp_pos)
14600       NEXT J
14610    NEXT I
14620    DISP "FILTERING DONE"
14630    DEALLOCATE B(*)
14640    DEALLOCATE Filter_temp_2(*)
14650    DEALLOCATE H1(*)
14660    RETURN
14670 !
14680 ! ==============================================================
14690 !   FILTER DESIGN
14700 ! ==============================================================
14710 Filter_design:    !
14720    RAD
14730    W=1000
14740    Ripple=.115
14750    Rejection=40
14760    Upper_limit=50
14770    Lower_limit=150
14780    Post_filter_flg=0
14790    GOSUB Calc_filter
14800    Pre_size=Filter_size
14810    PRINT "NUMBER OF TERMS IN PRE-FILTER ";Filter_size*2+1
14820    DEALLOCATE Pre_filter(*)
14830    ALLOCATE REAL Pre_filter(-Pre_size:Pre_size)
14840    FOR I=-Pre_size TO Pre_size
14850       Pre_filter(I)=Filter(ABS(I))
14860    NEXT I
14870    DEALLOCATE Filter(*)
14880    !
14890    Ripple=.115
14900    Rejection=40
14910    Upper_limit=50
14920    Lower_limit=75
14930    Post_filter_flg=1
14940    GOSUB Calc_filter
14950    Post_size=Filter_size
14960    PRINT "NUMBER OF TERMS IN POST-FILTER  ";Filter_size*2+1
14970    DEALLOCATE Post_filter(*)
14980    ALLOCATE REAL Post_filter(-Post_size:Post_siz:)
14990    FOR I=-Post_size TO Post_size
15000       Post_filter(I)=Filter(ABS(I))
15010    NEXT I
15020    DEALLOCATE Filter(*)
15030    !
15040    Y$=" "
15050    INPUT "DO YOU LIKE THIS FILTER DESIGN? Y or N",Y$
15060    IF Y$="N" THEN Filter_design
15070    Filter_flag=1
15080    PRINT CHR$(12)
15090    DEG
15100    RETURN
15110 !
15120 ! ==============================================================
15130 !   CALCULATE FILTER
15140 ! ==============================================================
15150 Calc_filter:    !
15160    W=Scan_rate
15170    IF NOT Post_filter_flg THEN
15180       DISP " DESIGN DATA FOR PRE-FILTER --- ";
```

```
15190    ELSE
15200       W=.25*W
15210       DISP "DESIGN DATA FOR POST-FILTER --- ";
15220    END IF
15230    INPUT "Ripple, dB: ",Ripple
15240    INPUT "Rejection, dB: ",Rejection
15250    INPUT "Upper Limit of Pass Band, Hz: ",Upper_limit
15260    INPUT "Lower Limit of Stop Band, Hz: ",Lower_limit
15270    Because=ABS(Lower_limit-Upper_limit)
15280    Lower_limit=Upper_limit+Because/2
15290    Ripple=10^(.05*Ripple)
15300    Rejection=10^(-.05*Rejection)
15310    Ratio=MIN(Rejection,(Ripple-1)/(Ripple+1))
15320    Ratio=-20*LGT(Ratio)
15330    E=0
15340    IF Ratio>50 THEN E=.1102*(Ratio-8.7)
15350    IF Ratio>21 AND Ratio<=50 THEN E=.5842*(Ratio-21)^.4+.07886*(Ratio-21)
15360    IF E=0 THEN
15370       Ix(2)=1
15380    ELSE
15390       Ix(2)=FNI(E)
15400    END IF
15410    D=.9222
15420    IF Ratio>21 THEN D=(Ratio-7.95)/14.36
15430    Filter_size=INT(D*W/Because+1)
15440    IF Filter_size MOD 2=0 THEN Filter_size=Filter_size+1
15450    Filter_size=(Filter_size-1)/2
15460    ALLOCATE REAL Filter(0:Filter_size)
15470    Filter(0)=Lower_limit*2/W
15480    Total_filter=Filter(0)
15490    FOR I=1 TO Filter_size
15500       Filter(I)=SIN(Lower_limit*I*2*PI/W)/(PI*I)
15510       X=E*SQR(1-(I/Filter_size)^2)
15520       IF X=0 THEN
15530          Ix(1)=1
15540       ELSE
15550          Ix(1)=FNI(X)
15560       END IF
15570       Filter(I)=Filter(I)*Ix(1)/Ix(2)
15580       Total_filter=Total_filter+2*Filter(I)
15590    NEXT I
15600    FOR I=0 TO Filter_size
15610       Filter(I)=Filter(I)/Total_filter
15620    NEXT I
15630    RETURN
15640 !
15650 !. ============================================================
15660 !   DATA CONVERT
15670 ! ============================================================
15680 Data_convert:!
15690    DISP "CONVERTING DATA TO ONES' COMPLIMENT"
15700    ALLOCATE INTEGER Conv(1:7000,1:18)
15710    MAT Signals= Signals+(30000)
15720    MAT Signals= Signals+(2767)
15730    MAT Conv= (2047)
15740    MAT Conv= Signals>Conv
15750    MAT Conv= Conv*(-4096)
15760    MAT Signals= Signals+Conv
15770    DEALLOCATE Conv(*)
15780    DISP ""
15790    RETURN
15800    !
15810    !
15820    DISP "SUBTRACTING ELECTRICAL BASELINE"
15830    Data_pointer=0
15840 !  INTEGER G(1:18,1:7000)
```

```
15850     FOR I=1 TO 18
15860 !      REDIM G(1:19-I,1:7000)
15870        MAT G= (Baseline(19-I))
15880     NEXT I
15890 !   REDIM G(1:18,1:7000)
15900     MAT Conv= TRN(G)
15910     MAT Signals= Signals+Conv
15920     Timeb=TIMEDATE
15930     PRINT Timeb-Timea
15940 !   DEALLOCATE Conv(*)
15950     DISP "PUTTING DATA IN CHRONOLOGICAL ORDER"
15960     ALLOCATE INTEGER Conv1(1:7000)
15970     J=0
15980     FOR I=Data_pointer+1 TO 7000
15990        J=J+1
16000        Conv1(J)=I
16010     NEXT I
16020     FOR I=1 TO Data_pointer
16030        J=J+1
16040        Conv1(J)=I
16050     NEXT I
16060     MAT REORDER Signals BY Conv1
16070   ! DEALLOCATE Conv1(*)
16080     Timefin=TIMEDATE
16090     PRINT Timefin-Timeinit
16100     DISP ""
16110     RETURN
16120 ! ============================================================
16130 !    DUMP EXPANDED GRAPHICS
16140 ! ============================================================
16150 Dump_expanded:!
16160     DUMP DEVICE IS 701,EXPANDED
16170     DUMP GRAPHICS
16180     RETURN
16190 !
16200 ! ============================================================
16210 !     DUMP GRAPHICS
16220 ! ============================================================
16230 Dump_graphics:!
16240     DUMP DEVICE IS 701
16250     DUMP GRAPHICS
16260     RETURN
16270                !
16280 ! ============================================================
16290 ! STATISTICS ROUTINES
16300 ! ============================================================
16310 Statistics:!
16320     OFF KEY
16330     ON KEY 0 LABEL "SELECT POINT",3 GOSUB Select_point
16340     ON KEY 1 LABEL " ",3 GOSUB Idle_stats
16350     ON KEY 2 LABEL "ORIENTATION",3 GOSUB Orientation
16360     ON KEY 3 LABEL "TORQUE AREA",3 GOSUB Torque_area
16370     ON KEY 4 LABEL " ",3 GOSUB Idle_stats
16380     ON KEY 5 LABEL " ",3 GOSUB Idle_stats
16390     ON KEY 6 LABEL " ",3 GOSUB Idle_stats
16400     ON KEY 7 LABEL " ",3 GOSUB Idle_stats
16410     ON KEY 8 LABEL " ",3 GOSUB Idle_stats
16420     ON KEY 9 LABEL "EXIT",3 GOSUB Exit_stats
16430     !
16440     Exit_stats=0
16450 Wait_loop_stats:   !
16460     IF NOT Exit_stats THEN Wait_loop_stats
16470     !
16480     Orient_flag=0
16490     Torque_flag=0
16500     !
```

```
16510    GOSUB Main_keys
16520    RETURN
16530 !
16540 ! ============================================================
16550 !    IDLE  STATS LOOP - DO NOTHING
16560 ! ============================================================
16570 Idle_stats:   !
16580    RETURN
16590 ! ============================================================
16600 !    EXIT STATISTICS ROUTINE
16610 ! ============================================================
16620 Exit_stats:    !
16630    Exit_stats=1
16640    RETURN
16650 !
16660 ! ============================================================
16670 !    ORIENTATION ANGLE OF PROPELLER
16680 ! ============================================================
16690 Orientation:   !
16700    Orient_flag=1
16710    Number_of_times=0
16720    MAT Times= (0)
16730    RETURN
16740 !
16750 ! ============================================================
16760 !    TORQUE AREA
16770 ! ============================================================
16780 Torque_area:   !
16790    IF Channel_no<>9 THEN
16800       DISP "NOT THE TORQUE CHANNEL YOU SILLY BURGER"
16810       BEEP
16820       GOSUB Exit_stats
16830       RETURN
16840    END IF
16850    Torque_flag=1
16860    Number_of_times=0
16870    MAT Times= (0)
16880    RETURN
16890 !
16900 ! ============================================================
16910 !    SELECT POINT
16920 ! ============================================================
16930 Select_point:   !
16940    IF Torque_flag AND Number_of_times>=2 THEN RETURN
16950    IF Orient_flag AND Number_of_times>=3 THEN RETURN
16960    Number_of_times=Number_of_times+1
16970    Times(Number_of_times)=Current_record
16980    IF Torque_flag AND Number_of_times=2 THEN GOSUB Calc_torque
16990    IF Orient_flag AND Number_of_times=3 THEN GOSUB Calc_orient
17000    RETURN
17010 !
17020 ! ============================================================
17030 !    CALCULATE ORIENTATION ANGLE OF PROPELLER
17040 ! ============================================================
17050 Calc_orient:   !
17060    MAT SORT Times
17070    Start_time=Times(1)
17080    GOSUB Find_prop_angle
17090    Prop_angle(1)=(Found_angle+60) MOD 360
17100    Start_time=Times(2)
17110    GOSUB Find_prop_angle
17120    Prop_angle(2)=(Found_angle+60) MOD 360
17130    Start_time=Times(3)
17140    GOSUB Find_prop_angle
17150    Prop_angle(3)=(Found_angle+60) MOD 360
17160    !
```

```
17170    PRINT "ANGLE 1: ";Prop_angle(1);"  ANGLE 2: ";Prop_angle(2);"  ANGLE 3:
 ";Prop_angle(3)
17180    INPUT "WOULD YOU LIKE TO SAVE TO DISC THIS DELIGHTFUL DATUR",R$
17190    IF UPC$(R$[1,1])="Y" THEN GOSUB Save_prop_angle
17200    Orient_flag=0
17210    RETURN
17220 !
17230 ! ==========================================================
17240 !   FIND PROPELLER ANGLES
17250 ! ==========================================================
17260 Find_prop_angle:    !
17270    !
17280    FOR I=1 TO Numb_of_pulse
17290       IF Rpm_pulse(I)>Start_time THEN Start_pulse
17300    NEXT I
17310 Start_pulse:        !
17320    Found_angle=(Start_time-Rpm_pulse(I-1))/(Rpm_pulse(I)-Rpm_pulse(I-1))*3
60
17330    RETURN
17340 !
17350 ! ==========================================================
17360 !   CALCULATE TORQUE AREA
17370 ! ==========================================================
17380 Calc_torque:    !
17390    IF Times(2)<=Times(1) THEN
17400       Times(3)=Times(2)
17410       Times(2)=Times(1)
17420       Times(1)=Times(3)
17430       Times(3)=0
17440    END IF
17450    Start_height=Signals(Times(1),9)
17460    Finish_height=Signals(Times(2),9)
17470    Current_height=Start_height
17480    Total_height=.5*(Start_height-Finish_height)*(Times(2)-Times(1))
17490    FOR I=Times(1)+1 TO Times(2)
17500       Last_height=Current_height
17510       Current_height=Signals(I,9)
17520       Total_height=Total_height+MIN(Current_height,Last_height)-First_heig
ht+.5*ABS(Current_height-Last_height)
17530    NEXT I
17540    Total_area=Total_height/Scan_rate*Slope(9)
17550    PRINT "TOTAL AREA UNDER TORQUE CURVE BETWEEN POINTS SELECTED: ";Total_a
rea
17560    INPUT "WOULD YOU LIKE THIS SAVE TO DISC? Y or N",R$
17570    IF UPC$(R$[1,1])="Y" THEN GOSUB Save_torque
17580    Torque_flag=0
17590    RETURN
17600 !
17610 ! ==========================================================
17620 !   SAVE TORQUE
17630 ! ==========================================================
17640 Save_torque:    !
17650    GOSUB Find_min_max
17660    INPUT "INSTALL TORQUE DISC IN THE LEFT-HAND DRIVE, CONTINUE",R$
17670 Torque_here:        !
17680    Torque_number=Torque_number+1
17690    File$="TORQUE"&VAL$(Torque_number)
17700    ON ERROR GOTO Torque_error
17710    DISP "CREATING TORQUE FILE: ";Torque_number
17720    CREATE BDAT File$&":INTERNAL,4,1",5
17730    OFF ERROR
17740    ASSIGN @Data_file TO File$&":INTERNAL,4,1"
17750    OUTPUT @Data_file;Title$,Dates$,Times$,N_channels,Nscans,Scan_rate,Int_
data,Int_pointer,Min_value(*),Max_value(*),Mean_value(*),Times(*),Total_area
17760    ASSIGN @Data_file TO *
17770    RETURN
```

```
17780 !
17790 ! =============================================================
17800 !    TORQUE DISC DRIVE ERRORS
17810 ! =============================================================
17820 Torque_error:   !
17830    IF ERRN=54 THEN Torque_here
17840    DISP ERRM$;
17850    INPUT "FIX, THEN CONTINUE",R$
17860    Torque_number=Torque_number-1
17870    GOTO Torque_here
17880 !
17890 ! =============================================================
17900 !    SAVE ORIENTATION ANGLES
17910 ! =============================================================
17920 Save_prop_angle:    !
17930    GOSUB Find_min_max
17940    Impact_code$=""
17950    Numb_impacts=0
17960    INPUT "INSTALL THE ORIENTATION DISC IN THE LEFT-HAND DRIVE, CONTINUE",R
$
17970 Orient_here:       !
17980    Orient_number=Orient_number+1
17990    File$="ORIENT"&VAL$(Orient_number)
18000    ON ERROR GOTO Orient_error
18010    DISP "CREATING ORIENTATION FILE: ";Orient_number
18020    CREATE BDAT File$,5
18030    OFF ERROR
18040    ASSIGN @Data_file TO File$
18050    OUTPUT @Data_file;Title$,Times$,Dates$,N_channels,Nscans,Scan_rate,Int_
data,Int_pointer,Min_value(*),Max_value(*),Mean_value(*),Times(*),Prop_angle(*)
18060    INPUT "ENTER THE NUMBER OF IMPACTS IN THIS SET.",Numb_impacts
18070    INPUT "ENTER THE IMPACT CODE. IE. Milling or Blockage - M or B",Impact_
code$
18080    OUTPUT @Data_file;Channel_no,Numb_impacts,Impact_code$
18090    ASSIGN @Data_file TO *
18100    RETURN
18110 !
18120 ! =============================================================
18130 !    ORIENTATION DISC ERRORS
18140 ! =============================================================
18150 Orient_error:   !
18160    IF ERRN=54 THEN Orient_here
18170    DISP ERRM$;
18180    INPUT "FIX, THEN CONTINUE",R$
18190    Orient_number=Orient_number-1
18200    GOTO Orient_here
18210 !
18220 ! =============================================================
18230 !    FIND MIN, MAX AND MEAN OF DATA BETWEEN SPECIFIED TIMES
18240 ! =============================================================
18250 Find_min_max:   !
18260    Start_time=Times(1)
18270    IF Torque_flag THEN
18280       Finish_time=Times(2)
18290    ELSE
18300       Finish_time=Times(3)
18310    END IF
18320    Time_diff=Finish_time-Start_time+1
18330    FOR I=1 TO 18
18340       Min_value(I)=2500
18350       Max_value(I)=-2500
18360       Mean_value(I)=0
18370       FOR J=Start_time TO Finish_time
18380          Min_value(I)=MIN(Min_value(I),Signals(J,I))
18390          Max_value(I)=MAX(Max_value(I),Signals(J,I))
18400          Mean_value(I)=Mean_value(I)+Signals(J,I)
```

```
18410      NEXT J
18420      Mean_value(I)=Mean_value(I)/Time_diff*Slope(I)+Offset(I)
18430      Min_value(I)=Min_value(I)*Slope(I)+Offset(I)
18440      Max_value(I)=Max_value(I)*Slope(I)+Offset(I)
18450   NEXT I
18460   IF Calculate_flag THEN
18470      FOR I=19 TO 21
18480         Min_value(I)=30000
18490         Max_value(I)=-30000
18500         Mean_value(I)=0
18510         FOR J=Start_time TO Finish_time
18520            Min_value(I)=MIN(Min_value(I),K(J,I))
18530            Max_value(I)=MAX(Max_value(I),K(J,I))
18540            Mean_value(I)=Mean_value(I)+K(J,I)
18550         NEXT J
18560         Mean_value(I)=Mean_value(I)/Time_diff
18570      NEXT I
18580   END IF
18590   Min_value(34)=2000
18600   Max_value(34)=0
18610   Mean_value(34)=0
18620   FOR J=Start_time TO Finish_time
18630      Min_value(34)=MIN(Min_value(34),Rpm(J))
18640      Max_value(34)=MAX(Max_value(34),Rpm(J))
18650      Mean_value(34)=Mean_value(34)+Rpm(J)
18660   NEXT J
18670   Mean_value(34)=Mean_value(34)/Time_diff
18680   RETURN
18690 !
18700 ! ============================================================
18710 !   THE END
18720 ! ============================================================
18730 The_end:    !
18740   END
18750 !
18760 ! ============================================================
18770 !   FUNCTION I
18780 ! ============================================================
18790   DEF FNI(P1)
18800      S=1
18810      U=1
18820      V=0
18830      V=V+2
18840      U=U*P1^2/V^2
18850      S=S+U
18860      IF U>=S*2.E-8 THEN 18830
18870      RETURN S
18880   FNEND
```

# APPENDIX H
# MV ROBERT LEMEUR PROPULSION TRAIN TORSIONAL AND LONGITUDINAL MODEL DEVELOPMENT

## TORSIONAL MODEL (See Figure 10.2.1)

List of Parameters:

| Location | J<br>kg.m$^2$ | $K_T$<br>KN.m/rad. |
|---|---|---|
| 1 | 413 | 581 |
| 2 | 146 | 413 |
| 3 | 274 | 18,950 |

**NOTES**:

A) J1 includes added mass.

B) J1 = 304 kg.m$^2$ in air.

Equations of Motion:

$$[J][\ddot{\theta}] + [G_T][\dot{\theta}] + [C_T][\dot{\theta}] + [K_T][\theta] = [F_T]$$

Where:
$[J]$ = Mass moment of inertia matrix
$[G_T]$ = Shaft damping matrix (proportional to $[K_T]$)
$[C_T]$ = Propeller damping matrix (only one non-zero element)
$[K_T]$ = Torsional stiffness matrix
$[F_T]$ = Force matrix (torque on propeller blade)
$[\theta]$ = Twist of shaft at each node

Solution to the Equation of Motion:

Solve free vibration problem to obtain the natural frequencies and subsequent eigen vectors;

Each column of the modal matrix [P] is an eigen vector

$$[P][Y] = [\theta], \text{ and;}$$

Substituting [P][Y] for $[\theta]$ and pre-multiplying by $[P]^T$ decouples the equations and results in three independent second order differential equations.

$$Y_1 + 2(\gamma_1 + \gamma_2)W_1 Y_1 + W_1^2 Y_1 = C_1 M_t$$

$$Y_2 + 2\ \gamma_1 W_2 Y_2 + W_2^2 Y_2 = C_2 M_t$$

$$Y_3 + 2\ \gamma_1 W_3 Y_3 + W_3^2 Y_3 = C_3 M_t$$

$\gamma_1$ = Shaft damping ratio
$\gamma_2$ = Propeller damping ratio

Any torque $M_t$ can be input, and the solution to each equation can be solved using Runge-Kutta method order four.

To determine rotation:

$$[\theta] = [P][Y]$$

To determine torque on the intermediate shaft:

$$T = (K_1)(\theta_2 - \theta_1)$$

The damping due to the propeller blade and shafting is varied until the torque wave form calculated agrees with that measured on the shaft.

LONGITUDINAL MODEL (See Figure 10.3.1)

List of Parameters

| Location | M<br>kg | K<br>N/m |
|---|---|---|
| 1 | 7000 | $9.71 \times 10^8$ |
| 2 | 8800 | $9.71 \times 10^8$ |
| 3 | 5600 | $9.71 \times 10^8$ |

Equations of Motion:

$$[M][\ddot{X}] + [G_L][\dot{X}] + [C_L][\dot{X}] + [K_T][X] = [F_L]$$

Solution to the Equation of Motion:

Same method as torsional model resulting in the following equations:

$$Y_1 + 2(\gamma_1 + \gamma_2)W_1Y_1 + W_1^2\gamma_1 = C_1F_t$$

$$Y_2 + 2\ \gamma_1W_2Y_2 + W_2^2Y_2 = C_2F_t$$

$$Y_3 + 2\ \gamma_1W_3Y_3 + W_3^2Y_3 = C_3F_t$$

$\gamma_1$ = Shaft damping ratio

$\gamma_2$ = Propeller damping ratio

Any thrust $F_t$ can be input. and the solution to each equation can be solved using Runge-Kutta method order four.

To determine movement of shaft:

Approximations

1. $[P]T[CT][P] = \begin{matrix} A & 0 & 0 \\ 0 & 0 & 0 \end{matrix}$

   Where A = Constant

2. Shaft is fixed for torsion at the flywheel.

   $[X] = [P][Y]$

To determine thrust:

$$F = (K_3)(-X_3)$$

The damping due to the propeller blade and shafting is varied until the thrust wave form calculated agrees with that measured on the shaft.

Approximations

1. $[P]^T[C_L][P] = \begin{matrix} A & 0 & 0 \\ 0 & 0 & 0 \end{matrix}$

   Where: A = Constant

2. Shaft is fixed at gear box.

# APPENDIX I

# LISTING OF PROGRAMS

"THRUST"

"TORQUE"

```
10    ! PROGRAM THRUST BY DNBC 84-10-31
20    ! THE EQUATION OF MOTION FOR THE THRUST PROPULSION TRAIN OF THE ROBERT
30    ! LEMEUR IS SOVLED, USING THE MODAL SUPERPOSITION METHOD AND THE
40    ! RUNGE-KUTTA FOURTH ORDER METHOD.
50    ! THERE ARE THREE DEGREES OF FREEDOM IN THE SIMPLIFIED MODEL.
60    !
70    ! THE EQUAION OF MOTION IS: [M](a)+[Ct](v)+[G](v)+[K](x)=(F)
80    !
90    ! [M] IS THE MASS MATRIX
100   ! [G] IS THE DAMPING MATRIX (PROPORTIONAL TO THE STIFFNESS MATRIX [K])
110   ! [Ct] IS THE PROPELLER DAMPING MATRIX
120   ! [K] IS THE STIFFNESS MATRIX
130   ! (a) IS THE ACCELERATION MATRIX
140   ! (v) IS THE VELOCITY MATRIX
150   ! (x) IS THE DISPLACEMENT MATRIX
160   ! (F) IS THE FORCING FUNCTION MATRIX
170   !
180   !
190 Start:  !
200   OPTION BASE 1
201   DEG
210   REAL T(4),Y(4),X(4),F(4)
220   REAL Tt(3000,3),Yy(3000,3),Zz(3000,3),M(3000)
230   REAL Theta1(3000),Theta2(3000),Theta3(3000),Torque(3000)
231   DIM Title$[30]
240   !
250   K1=9.71E8              ! STIFFNESS OF SHAFTING AT GAUGES (NM/RAD)
260   W1=25684                 !FIRST NATURAL FREQUENCY SQUARED (RAD/SEC)^2
270   W2=228484                !SECOND NATURAL FREQUENCY SQUARED (RAD/SEC)^2
280   W3=451584                !THIRD NATURAL FREQUENCY SQUARED (RAD/SEC)^2
290   !
300 Main:  !
310   PRINTER IS 16
320   PRINT PAGE
330   GOSUB Input_data
340   GOSUB Runge_kutta
350   BEEP
360   BEEP
370   GOSUB Solution
380   GOSUB Plot_modes
390   GOSUB Plot_solution
391   DISP "PUSH CONT "
392   PAUSE
395   GOSUB Dump_graphics
400   PRINT PAGE
410   PRINT LIN(10)
420   Q$=""
430   INPUT "DO YOU WANT TO RUN ANOTHER CASE?(Y,N)",Q$
440   IF Q$="Y" THEN GOTO Start
450   PRINT "*********************************************"
460   PRINT "          FINISHED PROGRAM"
470   PRINT "*********************************************"
480   STOP
490   END
500   !
510 Input_data:  !
520   INPUT "INPUT THE DATE (YY/MM/DD)",Date$
530   INPUT "INPUT THE TEST NUMBER",Test_no
540   INPUT "INPUT THE TIME INCREMENT",H
550   INPUT "INPUT THE NUMBER OF TIME INCREMENTS (10-3000)",Points
560   INPUT "INPUT THE PROPELLER DAMPING RATIO (0-1)",Dp
570   INPUT "INPUT THE SHAFT DAMPING RATIO(0-1)",Ds
580   INPUT "INPUT THE TIME AT FIRST IMPULSE",Ti
590   INPUT "INPUT THE LENGTH OF IMPULSE 1 AND THE MAXIMUM FORCE (SEC.,KN)",Lti,
M1
600   INPUT "INPUT THE TIME AT SECOND IMPULSE",Ti1
```

```
610   INPUT "INPUT THE LENGTH OF IMPULSE 2 AND THE MAXIMUM FORCE (SEC.,KN)",Lti1
,M2
620   INPUT "INPUT THE TIME AT THIRD IMPULSE",Ti2
630   INPUT "INPUT THE LENGTH OF IMPULSE 3 AND THE MAXIMUM FORCE (SEC.,KN)",Lti2
,M3
640   !
650   RETURN
660 Runge_kutta:  !
670   DISP "INTEGRATING DIFFERENTIAL EQUATIONS"
680   FOR K=1 TO 3
690     FOR J=1 TO Points-1
700       IF J=1 THEN
710         I=1
720         T(1)=Tt(1,K)=0
730         Yy(1,K)=0
740         Zz(1,K)=0
750         Y(1)=0
760         X(1)=0
770         GOSUB Load_time
780         IF K=1 THEN F(1)=FNF1(X(1),Y(1),M(J))
790         IF K=2 THEN F(1)=FNF2(X(1),Y(1),M(J))
800         IF K=3 THEN F(1)=FNF3(X(1),Y(1),M(J))
810       ELSE
820         I=1
830         T(1)=Tt(J,K)
840         X(1)=Yy(J,K)
850         Y(1)=Zz(J,K)
860         GOSUB Load_time
870         IF K=1 THEN F(1)=FNF1(X(1),Y(1),M(J))
880         IF K=2 THEN F(1)=FNF2(X(1),Y(1),M(J))
890         IF K=3 THEN F(1)=FNF3(X(1),Y(1),M(J))
900       END IF
910   !
920       FOR I=2 TO 4
930         IF I=4 THEN Mult=2
940         IF (I=2) OR (I=3) THEN Mult=1
950         T(I)=Tt(J,K)+H*.5*Mult
960         X(I)=Yy(J,K)+Y(I-1)*H*.5*Mult
970         Y(I)=Zz(J,K)+F(I-1)*H*.5*Mult
980         GOSUB Load_time
990         IF K=1 THEN F(I)=FNF1(X(I),Y(I),M(J))
1000        IF K=2 THEN F(I)=FNF2(X(I),Y(I),M(J))
1010        IF K=3 THEN F(I)=FNF3(X(I),Y(I),M(J))
1020      NEXT I
1030  !
1040      Yy(J+1,K)=Yy(J,K)+H/6*(Y(1)+2*Y(2)+2*Y(3)+Y(4))
1050      Zz(J+1,K)=Zz(J,K)+H/6*(F(1)+2*F(2)+2*F(3)+F(4))
1060      Tt(J+1,K)=T(4)
1070    NEXT J
1080  NEXT K
1090  DISP "FINISHED INTEGRATING"
1100  !
1110 Equations: !
1120  ! EQUATIONS OF MOTION FOR MODAL SUPERPOSITION
1130  !
1140  DEF FNF1(X,Y,M)=M/13930-2*(Dp+Ds)*SQR(W1)*Y-W1*X       !FIRST MODE EQUATION
1150  DEF FNF2(X,Y,M)=-.462/3367*M-2*Ds*SQR(W2)*Y-W2*X            !SECOND MODE EQU
ATION
1160  DEF FNF3(X,Y,M)=.1182/1807*M-2*Ds*SQR(W3)*Y-W3*X             !THIRD MODE EQU
ATION
1170  RETURN
1180  !
1190 Load_time: ! LOAD ON PROPELLER BLADE AS A FUNCTION OF TIME
1200  ! M=LOAD ON PROPELLER BLADE IN Nm OR N
1210  ! T(I)= TIME IN SECONDS
1220  !
```

CANADIAN
MARINE
DRILLING
LIMITED

MEASUREMENT OF ICE
PROPELLER INTERACTION
PARAMETERS

TITLE:
"THRUST"

APPENDIX I

```
1230  M(J)=0
1231  ! IF (T(I)>=Ti) AND (T(I)<=Ti+Lti) THEN M(J)=M1*SIN((T(I)-Ti)/(2*Lti)*360)
1232  ! IF (T(I)>=Ti) AND (T(I)<=Ti+Lti) THEN M(J)=M1
1240  IF (T(I)>=Ti) AND (T(I)<=Ti+.5*Lti) THEN M(J)=M1*(T(I)-Ti)/(Lti*.5)
1250  IF (T(I)>=Ti+.5*Lti) AND (T(I)<=Ti+Lti) THEN M(J)=M1-M1*(T(I)-(Ti+.5*Lti))
/(Lti*.5)
1260  IF (Ti1<>0) AND (T(I)>=Ti1) AND (T(I)<=Ti1+.5*Lti1) THEN M(J)=M2*(T(I)-Ti1
)/(Lti1*.5)
1270  IF (Ti1<>0) AND (T(I)>=Ti1+.5*Lti1) AND (T(I)<=Ti1+Lti1) THEN M(J)=M2-M2*(
T(I)-(Ti1+.5*Lti1))/(Lti1*.5)
1280  IF (Ti2<>0) AND (T(I)>=Ti2) AND (T(I)<=Ti2+.5*Lti2) THEN M(J)=M3*(T(I)-Ti2
)/(Lti2*.5)
1290  IF (Ti2<>0) AND (T(I)>=Ti2+.5*Lti2) AND (T(I)<=Ti2+Lti2) THEN M(J)=M3-M3*(
T(I)-(Ti2+.5*Lti2))/(Lti2*.5)
1300  M(J)=M(J)*1000
1310  RETURN
1320  !
1330 Plot_modes: !
1340  PLOTTER IS "GRAPHICS"
1350  GRAPHICS
1360  K1=0
1370  INPUT "WHICH MODE SHAPE WOULD YOU LIKE PLOTTED (1,2,3) OR PUSH CONT ",K1
1380  IF K1=0 THEN RETURN
1390  K=1
1400  GOSUB Plot_setup
1410    !
1420  MOVE Tt(1,K1),Yy(1,K1)
1430  FOR I=2 TO Points
1440    PLOT Tt(I,K1),Yy(I,K1),-1
1450  NEXT I
1460  MOVE .60*(Xmax-Xmin),.60*Ymax
1470  LABEL "Y"&VAL$(K1)
1480  PAUSE
1490  DISP "PUSH CONT"
1500  DISP ""
1510  Q$=""
1520  INPUT "DO YOU WANT TO DUMP THESE GRAPHS ?(Y,N)",Q$
1530  IF Q$="Y" THEN
1540    PRINTER IS 0
1550    PRINT LIN(3)
1560    PRINT "PLOTS OF MODAL RESPONSE FOR M.V. ROBERT LEMEUR PROPULSION SYSTEM"
1570    PRINT LIN(3)
1580    DUMP GRAPHICS
1590    EXIT GRAPHICS
1600    PRINT PAGE
1610    PRINTER IS 16
1620  ELSE
1630    EXIT GRAPHICS
1640  END IF
1650  Q$=""
1660  INPUT "DO YOU WANT TO PLOT THESE GRAPHS AGAIN?(Y,N)",Q$
1670  IF Q$="Y" THEN GOTO Plot_modes
1680  RETURN
1690  !
1700 Plot_solution: !
1730  PRINT "PLOT OF THRUST AND LOAD"
1740  PLOTTER IS "GRAPHICS"
1750  GRAPHICS
1760  FOR K=1 TO 2
1770    Title$="PROP. DISP. (M)"
1780    IF K=1 THEN Title$="PROPELLER LOAD (KN)"
1790    IF K=2 THEN Title$="SHAFT THRUST (KN)"
1800    GOSUB Plot_setup
1810    IF K=1 THEN MOVE Tt(1,1),M(I)*.001
1812    IF K=2 THEN MOVE Tt(1,1),Torque(I)
1820    FOR I=2 TO Points
```

```
1860       IF K=1 THEN PLOT Tt(I,1),M(I)*.001,-1
1870       IF K=2 THEN PLOT Tt(I,1),Torque(I),-1
1880     NEXT I
1890     MOVE .5*(Xmax+Xmin),.80*Ymax
1900     LABEL Title$
1910     PAUSE
1920     DISP "PUSH CONT"
1930     DISP ""
1940   NEXT K
1941   RETURN
1942   !
1943 Dump_graphics: !
1950   Q$=""
1960   INPUT "DO YOU WANT TO PLOT THESE GRAPHS AGAIN?(Y,N)",Q$
1970   IF Q$="Y" THEN GOTO Plot_solution
1980   EXIT GRAPHICS
1990   Q$=""
2000   INPUT "DO YOU WANT TO DUMP THESE GRAPHS ?(Y,N)",Q$
2010   IF Q$="Y" THEN
2020     PRINTER IS 0
2030     PRINT LIN(3)
2040     PRINT "PLOTS OF THRUST  FOR M.V. ROBERT LEMEUR PROPULSION SYSTEM MODEL"
2050     PRINT LIN(2)
2060     PRINT "TEST ";Test_no
2070     PRINT "ANALYSIS DATE: ";Date$
2080     PRINT LIN(2)
2090     DUMP GRAPHICS
2100     PRINT LIN(2)
2110     PRINT "DAMPING COEFFICIENT FOR SHAFT:    ";Ds
2120     PRINT "DAMPING COEFFICIENT FOR PROP.:    ";Dp
2130     PRINT "TIME INCREMENT:                   ";H
2140     PRINT "TIME AT FIRST IMPULSE (SEC.)      ";Ti
2150     PRINT "LENGTH OF FIRST IMPULSE (SEC.)    ";Lti;"   MAX. PROPELLER LOAD (K
N): ";M1
2160     IF Ti1<>0 THEN PRINT "TIME AT SECOND IMPULSE (SEC.)     ";Ti1
2170     IF Ti1<>0 THEN PRINT "LENGTH OF SECOND IMPULSE (SEC.)  ";Lti1;"   MAX. P
ROPELLER LOAD (KN): ";M2
2180     PRINT PAGE
2190     PRINTER IS 16
2200   END IF
2210   RETURN
2220   !
2280 Solution: !

2290   DISP "CALCULATING TWIST AND LOAD"
2300   FOR I=1 TO Points
2310     Theta1(I)=1*Yy(I,1)-.462*Yy(I,2)+.1182*Yy(I,3)
2320     Theta2(I)=.8148*Yy(I,1)+.2996*Yy(I,2)-.2665*Yy(I,3)
2330     Theta3(I)=.4400*Yy(I,1)+.4400*Yy(I,2)+.4400*Yy(I,3)
2340     Torque(I)=-K1*Theta3(I)*.001   !SHAFT TORQUE IN KNm (KN)
2350   NEXT I
2360   DISP ""
2370   RETURN
2380   !
2390 Plot_setup: !
2400   LOCATE 20,110,10+(K-1)*50,50+(K-1)*50
2410   FRAME
2420   MOVE 40,0
2430   LABEL "TIME (Seconds)"
2440   INPUT "INPUT SCALE (XMIN,XMAX,YMIN,YMAX)",Xmin,Xmax,Ymin,Ymax
2450   SCALE Xmin,Xmax,Ymin,Ymax
2460   AXES Xmax/50,Ymax/10,Xmin,Ymin,5,2
2470   AXES Xmax/50,Ymax/10,Xmin,Ymax,5,2
2480   AXES Xmax/50,Ymax/10,Xmax,Ymin,5,2
2490   FIXED 2
2500   LORG 5
```

```
2510 X=Xmin
2520 Y=Ymin
2530 IF K=1 THEN
2540   FOR I=1 TO 10
2550     X=X+ABS(Xmax-Xmin)/10
2560     X$=VAL$(X)
2570     MOVE X,Ymin-.07*ABS(Ymax-Ymin)
2580     LABEL X$
2590   NEXT I
2600 END IF
2610   !
2620 LORG 8
2630 FIXED 0
2640 FOR I=1 TO 5
2650   Y$=VAL$(Y)
2660   MOVE Xmin,Y
2670   LABEL Y$&"  "
2680   Y=Y+ABS(Ymax-Ymin)/5
2690 NEXT I
2700 STANDARD
2710 RETURN
```

| | | |
|---|---|---|
| CANADIAN<br>MARINE<br>DRILLING<br>LIMITED | MEASUREMENT OF ICE<br>PROPELLER INTERACTION<br>PARAMETERS | TITLE:<br>"THRUST"<br>APPENDIX I |

```
10    ! PROGRAM "TORQUE" BY DNBC 84-10-31
20    ! THE EQUATION OF MOTION FOR THE TORQUE OF THE PROPULSION TRAIN
30    ! OF THE ROBERT LEMEUR IS SLOVED, USING THE MODAL SUPERPOSITION
40    ! METHOD AND THE RUNGE-KUTTA FOURTH ORDER METHOD.
50    ! THERE ARE THREE DEGREES OF FREEDOM IN THE SIMPLIFIED MODEL.
60    !
70    ! THE EQUAION OF MOTION IS: [J](a)+[Ct](w)+[G](w)+[K](o)=(F)
80    !
90    ! [J] IS THE MASS POLAR MOMENT OF INERTIA MATRIX
100   ! [G] IS THE DAMPING MATRIX (PROPORTIONAL TO THE STIFFNESS MATRIX [K])
110   ! [Ct] IS THE PROPELLER DAMPING MATRIX
120   ! [K] IS THE STIFFNESS MATRIX
130   ! (a) IS THE ANGULAR ACCELERATION MATRIX
140   ! (w) IS THE ANGULAR VELOCITY MATRIX
150   ! (o) IS THE ANGULAR DISPLACEMENT MATRIX
160   ! (F) IS THE FORCING FUNCTION MATRIX
170   !
180   !
190 Start:  !
200   OPTION BASE 1
201   DEG
210   REAL T(4),Y(4),X(4),F(4)
220   REAL Tt(3000,3),Yy(3000,3),Zz(3000,3),M(3000)
230   REAL Theta1(3000),Theta2(3000),Theta3(3000),Torque(3000)
231   DIM Title$[25]
240   !
250   K1=5.81E5                !TORSIONAL STIFFNESS OF SHAFTING AT GAUGES (NM/RAD)
260   W1=509                     !FIRST NATURAL FREQUENCY SQUARED (RAD/SEC)^2
270   W2=7639                    !SECOND NATURAL FREQUENCY SQUARED (RAD/SEC)^2
280   W3=70735                   !THIRD NATURAL FREQUENCY SQUARED (RAD/SEC)^2
330   !
340 Main:  !
350   PRINTER IS 16
360   PRINT PAGE
370   GOSUB Input_data
380   GOSUB Runge_kutta
390   BEEP
400   BEEP
410   GOSUB Solution
420   GOSUB Plot_modes
430   GOSUB Plot_solution
440   PRINT PAGE
450   PRINT LIN(10)
460   Q$=""
470   INPUT "DO YOU WANT TO RUN ANOTHER CASE?(Y,N)",Q$
480   IF Q$="Y" THEN GOTO Start
490   PRINT "************************************************"
500   PRINT "         FINISHED PROGRAM"
510   PRINT "************************************************"
520   STOP
530   END
540   !
550 Input_data:  !
560   INPUT "INPUT THE DATE (YY/MM/DD/)",Date$
570   INPUT "INPUT THE TEST NUMBER ",Test$
580   INPUT "INPUT THE TIME INCREMENT (.01-.001) ",H
590   INPUT "INPUT THE NUMBER OF TIME INCREMENTS (10-3000)",Points
600   INPUT "INPUT THE DAMPING RATIO FOR THE PROPELLER  (0-1)",Dp
610   INPUT "INPUT THE DAMPING RATIO FOR THE SHAFT (0-1)",Ds
620   INPUT "INPUT THE TIME OF FIRST IMPULSE",Ti
630   INPUT "INPUT THE LENGTH OF FIRST IMPULSE AND MAXIMUM VALUE (SEC.,KNm) ",Lt
i,M1
640   INPUT "INPUT THE TIME OF SECOND IMPULSE",Ti1
650   INPUT "INPUT THE LENGTH OF SECOND IMPULSE AND MAXIMUM VALUE (SEC.,KNm),",L
ti1,M2
```

```
660    INPUT "INPUT THE TIME OF THIRD IMPULSE",Ti2
670    INPUT "INPUT THE LENGTH OF THIRD IMPULSE AND MAXIMUM VALUE (SEC.,KNM)",Lti
2,M3
680    !
690    RETURN
700 Runge_kutta:  !
710    DISP "INTEGRATING DIFFERENTIAL EQUATIONS"
720    FOR K=1 TO 3
730      FOR J=1 TO Points-1
740        IF J=1 THEN
750          I=1
760          T(1)=Tt(1,K)=0
770          Yy(1,K)=0
780          Zz(1,K)=0
790          Y(1)=0
800          X(1)=0
810          GOSUB Load_time
820          IF K=1 THEN F(1)=FNF1(X(1),Y(1),M(J))
830          IF K=2 THEN F(1)=FNF2(X(1),Y(1),M(J))
840          IF K=3 THEN F(1)=FNF3(X(1),Y(1),M(J))
850        ELSE
860          I=1
870          T(1)=Tt(J,K)
880          X(1)=Yy(J,K)
890          Y(1)=Zz(J,K)
900          GOSUB Load_time
910          IF K=1 THEN F(1)=FNF1(X(1),Y(1),M(J))
920          IF K=2 THEN F(1)=FNF2(X(1),Y(1),M(J))
930          IF K=3 THEN F(1)=FNF3(X(1),Y(1),M(J))
940        END IF
950    !
960        FOR I=2 TO 4
970          IF I=4 THEN Mult=2
980          IF (I=2) OR (I=3) THEN Mult=1
990          T(I)=Tt(J,K)+H*.5*Mult
1000         X(I)=Yy(J,K)+Y(I-1)*H*.5*Mult
1010         Y(I)=Zz(J,K)+F(I-1)*H*.5*Mult
1020         GOSUB Load_time
1030         IF K=1 THEN F(I)=FNF1(X(I),Y(I),M(J))
1040         IF K=2 THEN F(I)=FNF2(X(I),Y(I),M(J))
1050         IF K=3 THEN F(I)=FNF3(X(I),Y(I),M(J))
1060       NEXT I
1070   !
1080       Yy(J+1,K)=Yy(J,K)+H/6*(Y(1)+2*Y(2)+2*Y(3)+Y(4))
1090       Zz(J+1,K)=Zz(J,K)+H/6*(F(1)+2*F(2)+2*F(3)+F(4))
1100       Tt(J+1,K)=T(4)
1110     NEXT J
1120   NEXT K
1130   DISP "FINISHED INTEGRATING"
1140   !
1150 Equations: !
1160   ! EQUATIONS OF MOTION FOR MODAL SUPERPOSITION
1170   !
1180   DEF FNF1(X,Y,M)=1.209E-3*M-2*(Dp+Ds)*SQR(W1)*Y-W1*X      !FIRST MODE EQUAT
ION
1190   DEF FNF2(X,Y,M)=-1.346E-3*M-2*Ds*SQR(W2)*Y-W2*X          !SECOND MODE EQUA
TION
1200   DEF FNF3(X,Y,M)=1.366E-4*M-2*Ds*SQR(W3)*Y-W3*X           !THIRD MODE EQUAT
ION
1210   RETURN
1220   !
1230 Load_time: ! TORQUE ON PROPELLER BLADE AS A FUNCTION OF TIME
1240   ! M=TORQUE ON PROPELLER BLADE IN Nm
1250   ! T(I)= TIME IN SECONDS
1260   !
1270   M(J)=0
```

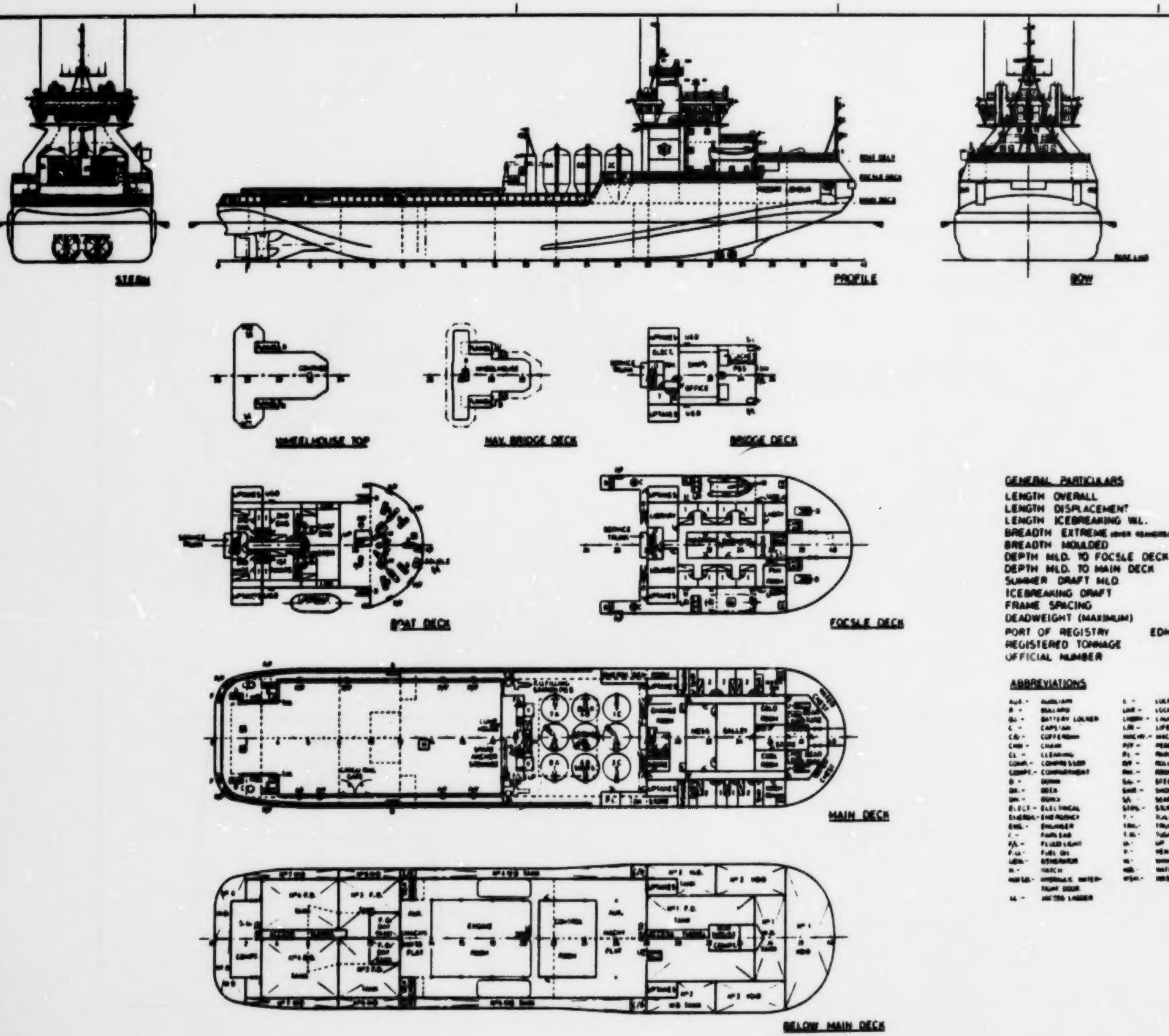
```
1275  ! IF (T(I)>=Ti) AND (T(I)<=Ti+Lti) THEN M(J)=M1*SIN((T(I)-Ti)/(Lti*2)*360)
1276  ! IF (T(I)>=Ti) AND (T(I)<=Ti+Lti) THEN M(J)=M1
1280  IF (T(I)>=Ti) AND (T(I)<=Ti+.5*Lti) THEN M(J)=M1*(T(I)-Ti)/(Lti*.5)
1290  IF (T(I)>Ti+.5*Lti) AND (T(I)<=Ti+Lti) THEN M(J)=M1-M1*(T(I)-(Ti+.5*Lti))/
(Lti*.5)
1300  IF (Ti1<>0) AND (T(I)>=Ti1) AND (T(I)<=Ti1+.5*Lti1) THEN M(J)=M2*(T(I)-Ti1
)/(Lti1*.5)
1310  IF (Ti1<>0) AND (T(I)>Ti1+.5*Lti1) AND (T(I)<=Ti1+Lti1) THEN M(J)=M2-M2*(T
(I)-(Ti1+.5*Lti1))/(Lti1*.5)
1320  IF (Ti2<>0) AND (T(I)>=Ti2) AND (T(I)<=Ti2+.5*Lti2) THEN M(J)=M3*(T(I)-Ti2
)/(Lti2*.5)
1330  IF (Ti2<>0) AND (T(I)>Ti2+.5*Lti2) AND (T(I)<=Ti2+Lti2) THEN M(J)=M3-M3*(T
(I)-(Ti2+.5*Lti2))/(Lti2*.5)
1340  M(J)=M(J)*1000
1440  RETURN
1450  !
1460 Plot_modes: !
1470  PRINT "PLOTS OF MODE SHAPES"
1480  PLOTTER IS "GRAPHICS"
1490  GRAPHICS
1500  K1=0
1510  INPUT "ENTER MODE SHAPE TO BE PLOTTED (1,2,3) OR PUSH CONT ",K1
1520  IF K1=0 THEN RETURN
1530  K=1
1540  GOSUB Plot_setup
1550    !
1560  MOVE Tt(1,K1),Yy(1,K1)
1570  FOR I=2 TO Points
1580    PLOT Tt(I,K1),Yy(I,K1),-1
1590  NEXT I
1600  MOVE .60*(Xmax-Xmin),.60*Ymax
1610  LABEL "Y"&VAL$(K1)
1620  PAUSE
1630  DISP "PUSH CONT"
1640  DISP ""
1650  Q$=""
1660  INPUT "DO YOU WANT TO DUMP THESE GRAPHS ?(Y,N)",Q$
1670  IF Q$="Y" THEN
1680    PRINTER IS 0
1690    PRINT LIN(3)
1700    PRINT "PLOTS OF MODAL RESPONSE FOR M.V. ROBERT LEMEUR PROPULSION SYSTEM"
1710    PRINT LIN(3)
1720    DUMP GRAPHICS
1730    EXIT GRAPHICS
1740    PRINT PAGE
1750    PRINTER IS 16
1760  ELSE
1770    EXIT GRAPHICS
1780  END IF
1790  Q$=""
1800  INPUT "DO YOU WANT TO PLOT ANOTHER MODE?(Y,N)",Q$
1810  IF Q$="Y" THEN GOTO Plot_modes
1820  RETURN
1830  !
1840 Plot_solution: !
1850  PRINT PAGE
1860  PRINT "PLOTS OF TORQUE VS TIME"
1870  PLOTTER IS "GRAPHICS"
1880  GRAPHICS
1890  FOR K=1 TO 2
1900    Title$="PROP. TWIST (RAD.)"
1910    IF K=1 THEN Title$="PROPELLER TORQUE (KNm)"
1920    IF K=2 THEN Title$="SHAFT TORQUE (KNm)"
1930    GOSUB Plot_setup
1940    MOVE Tt(1,I),Theta1(1)
1950    FOR I=2 TO Points
```

```
1990      IF K=1 THEN PLOT Tt(I,1),M(I)*.001,-1
2000      IF K=2 THEN PLOT Tt(I,1),Torque(I),-1
2010    NEXT I
2020    MOVE .5*(Xmax+Xmin),.90*Ymax
2030    LABEL Title$
2040    DISP "PUSH CONT"
2050    PAUSE
2060    DISP ""
2070  NEXT K
2080  Q$=""
2090  INPUT "DO YOU WANT TO PLOT THESE GRAPHS AGAIN?(Y,N)",Q$
2100  IF Q$="Y" THEN GOTO Plot_solution
2110  Q$=""
2120  INPUT "DO YOU WANT TO DUMP THESE GRAPHS ?(Y,N)",Q$
2130  EXIT GRAPHICS
2140  IF Q$="Y" THEN
2150    PRINTER IS 0
2160    PRINT LIN(5)
2170    PRINT "PLOTS OF TORQUE  FOR M.V. ROBERT LEMEUR PROPULSION SYSTEM MODEL"
2180    PRINT LIN(2)
2190    PRINT "TEST "&Test$
2200    PRINT "ANALYSIS DATE: "&Date$
2210    PRINT LIN(2)
2220    DUMP GRAPHICS
2230    PRINT LIN(2)
2240    PRINT "DAMPING RATIO  FOR THE SHAFT:      ";Ds
2250    PRINT "DAMPING RATIO  FOR THE PROPELLER: ";Dp
2260    PRINT "TIME INCREMENT (SEC.):            ";H
2270    PRINT "TIME AT FIRST IMPULSE (SEC.):     ";Ti
2280    PRINT "LENGTH OF FIRST IMPULSE (SEC.):   ";Lti;"   MAX. TORQUE (KNm): ";
M1
2290    IF Ti1<>0 THEN PRINT "TIME AT SECOND IMPULSE (SEC.):     ";Ti1
2300    IF Ti1<>0 THEN PRINT "LENGTH OF SECOND IMPULSE (SEC.):  ";Lti1;"   MAX.
TORQUE (KNm): ";M2
2310    IF Ti2<>0 THEN PRINT "TIME AT THIRD IMPULSE (SEC.):      ";Ti2
2320    IF Ti2<>0 THEN PRINT "LENGTH OF THIRD IMPULSE (SEC.):   ";Lti1;"   MAX.
TORQUE (KNm): ";M3
2330    PRINT PAGE
2340    PRINTER IS 16
2350  END IF
2360  RETURN
2370  !
2380 Solution: !

2390  DISP "CALCULATING TWIST AND TORQUE"
2400  FOR I=1 TO Points
2410    Theta1(I)=1.751*Yy(I,1)-.226*Yy(I,2)+2.157E-5*Yy(I,3)
2420    Theta2(I)=1.117*Yy(I,1)+1.0034*Yy(I,2)-1.063E-3*Yy(I,3)
2430    Theta3(I)=.0240*Yy(I,1)+.0240*Yy(I,2)+.0240*Yy(I,3)
2440    Torque(I)=K1*(Theta1(I)-Theta2(I))*.001   !SHAFT TORQUE IN KNm
2450  NEXT I
2460  DISP ""
2470  RETURN
2480  !
2490 Plot_setup: !
2500  LOCATE 20,120,10+(K-1)*50,50+(K-1)*50
2510  FRAME
2520  MOVE 40,0
2530  LABEL "TIME (Seconds)"
2540  INPUT "INPUT SCALE (XMIN,XMAX,YMIN,YMAX)",Xmin,Xmax,Ymin,Ymax
2550  SCALE Xmin,Xmax,Ymin,Ymax
2560  AXES Xmax/50,Ymax/10,Xmin,Ymin,5,2
2570  AXES Xmax/50,Ymax/10,Xmin,Ymax,5,2
2580  AXES Xmax/50,Ymax/10,Xmax,Ymin,5,2
2590  FIXED 2
2600  LORG 5
```

```
2610  X=Xmin
2620  Y=Ymin
2630  IF K=1 THEN
2640    FOR I=1 TO 10
2650      X=X+ABS(Xmax-Xmin)/10
2660      X$=VAL$(X)
2670      MOVE X,Ymin-.07*ABS(Ymax-Ymin)
2680      LABEL X$
2690    NEXT I
2700  END IF
2710    !
2720  LORG 8
2730  FIXED 0
2740  FOR I=1 TO 5
2750    Y$=VAL$(Y)
2760    MOVE Xmin,Y
2770    LABEL Y$&"  "
2780    Y=Y+ABS(Ymax-Ymin)/5
2790  NEXT I
2800  STANDARD
2810  RETURN
```

# APPENDIX J
# MACHINE DRAWINGS


STERN
PROFILE
BOW
WHEELHOUSE TOP
NAV. BRIDGE DECK
BRIDGE DECK
BOAT DECK
FOCSLE DECK
MAIN DECK
BELOW MAIN DECK
ENGINE ROOM
CONTROL ROOM
MESS
GALLEY
OFFICE

**GENERAL PARTICULARS**

| | |
|---|---|
| LENGTH OVERALL | 82·800 METRES |
| LENGTH DISPLACEMENT | 78·000 M |
| LENGTH ICEBREAKING W.L. | 79·125 M |
| BREADTH EXTREME (OVER FENDERS) | 19·034 M |
| BREADTH MOULDED | 18·000 M |
| DEPTH MLD. TO FOCSLE DECK | 10·500 M |
| DEPTH MLD. TO MAIN DECK | 7·500 M |
| SUMMER DRAFT MLD | 5·668 M |
| ICEBREAKING DRAFT | 5·500 M |
| FRAME SPACING | 2·000 M |
| DEADWEIGHT (MAXIMUM) | 2690·4 TONNES |
| PORT OF REGISTRY | EDMONTON, ALBERTA. |
| REGISTERED TONNAGE | 1501·49 |
| OFFICIAL NUMBER | 801810 |

**ABBREVIATIONS**

| | | | |
|---|---|---|---|
| AUX. - | AUXILIARY | L - | LOCKER |
| B - | BOLLARD | LKR - | LOCKER |
| BL - | BATTERY LOCKER | LNDRY - | LAUNDRY |
| C - | CAPSTAN | LR - | LIFERAFTS |
| CD - | COFFERDAM | MACHY. - | MACHINERY |
| CHN - | CHAIN | PF - | PEDESTAL FAIRLEAD |
| CL - | CLEANING | PL - | PAINT LOCKER |
| COMP. - | COMPRESSOR | RF - | ROLLER FAIRLEAD |
| COMPT. - | COMPARTMENT | RM. - | ROOM |
| D - | DOWN | SG. - | STEERING GEAR |
| DK. - | DECK | SHR. - | SHOWER |
| [illegible] | [illegible] | SL - | SEARCHLIGHT |
| ELECT. - | ELECTRICAL | STRS. - | STORES |
| EMERGY. - | EMERGENCY | T. - | TOILET |
| ENG. - | ENGINEER | TRK. - | TRUNK |
| F. - | FAIRLEAD | T.W. - | TUGGER WINCH |
| FL - | FLOODLIGHT | U. - | UP |
| F.O. - | FUEL OIL | V. - | VENT |
| GEN. - | GENERATOR | W. - | WINCH |
| H. - | HATCH | WB. - | WATER BALLAST |
| HWTD. - | HYDRAULIC WATER-TIGHT DOOR | WSH. - | WASH |
| IL - | INCLINED LADDER | | |

Burrard Yarrows Corporation

VANCOUVER

HULL 1·06 97·00

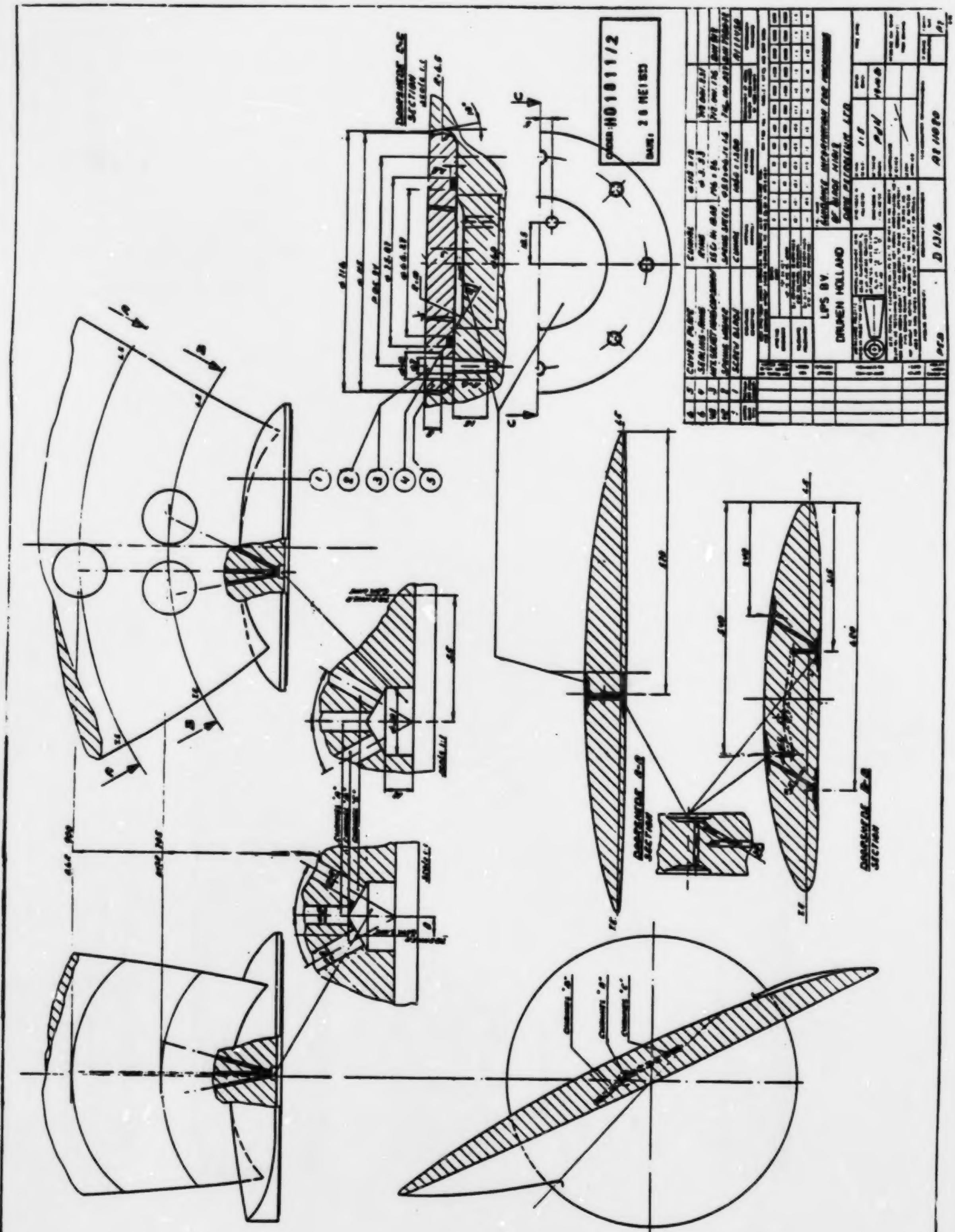
[illegible] DOME PETROLEUM LTD.

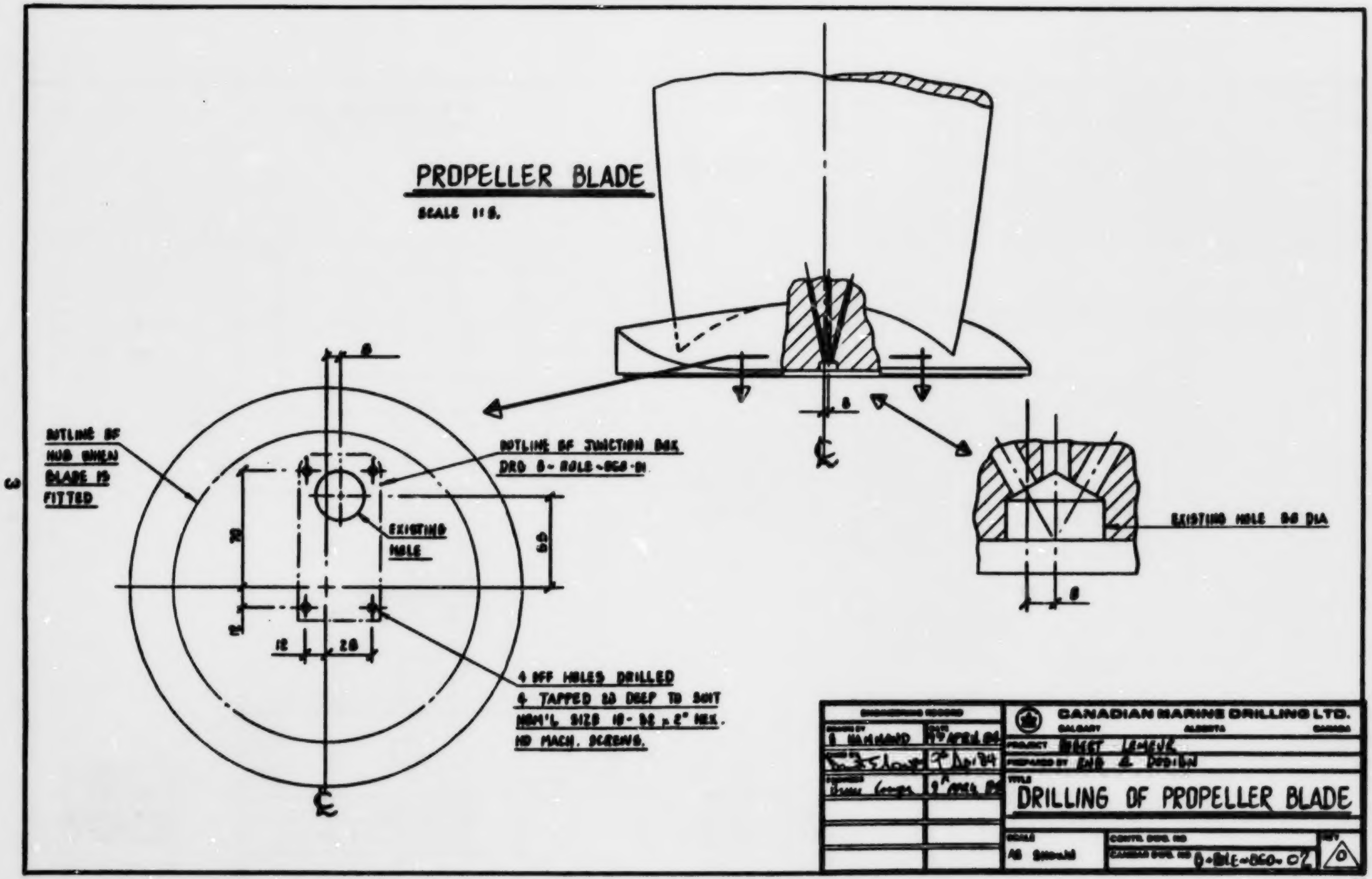
'ROBERT LEMEUR'

GENERAL ARRANGEMENT

SCALE 1:200

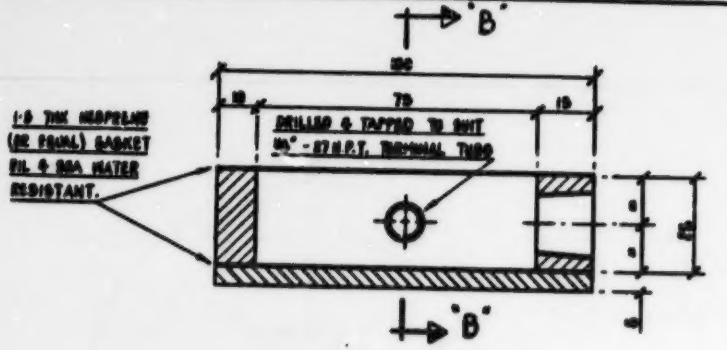
00·00·18


ORDER: H010111/2
DATE: 28 MEI 1953
DOORSNEDE C-C SECTION
DOORSNEDE B-B SECTION
DOORSNEDE A-A SECTION
LIPS BV.
DRUNEN HOLLAND
CUTTER PLATE
SEALING RING
SPRING WASHER
SCREW BLADE
D 1316

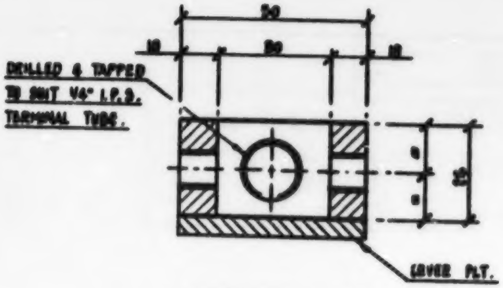

PROPELLER BLADE
SCALE 1:5.
OUTLINE OF HUB WHEN BLADE IS FITTED
OUTLINE OF JUNCTION BOX DRG B-BOLE-060-01
EXISTING HOLE
4 OFF HOLES DRILLED & TAPPED 23 DEEP TO SUIT NOM'L SIZE 10-32 x 2" HEX. HD MACH. SCREWS.
EXISTING HOLE 30 DIA
30
69
12
28
8
8
8
℄
℄

ENGINEERING RECORD
DRAWN BY S. HAMMOND — 1st APRIL 84
CHECKED BY — 2nd Apr/84
APPROVED — 9th APRIL 84

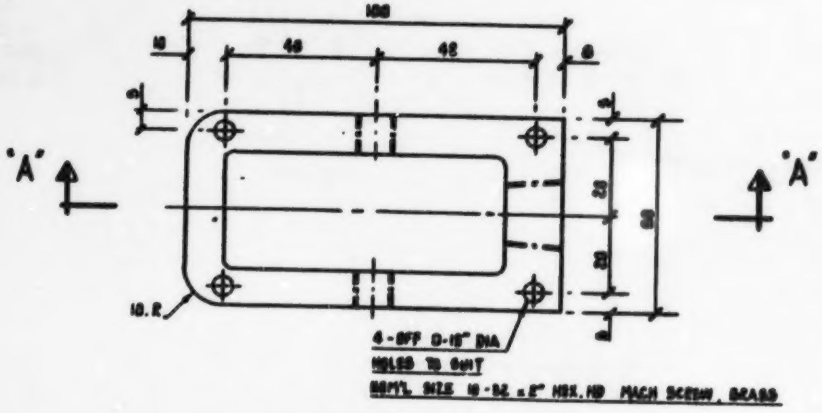
CANADIAN MARINE DRILLING LTD.
CALGARY ALBERTA CANADA
PROJECT [illegible] LEMEVE
PREPARED BY ENG & DESIGN
TITLE DRILLING OF PROPELLER BLADE
SCALE AS SHOWN
CONTR. DWG. NO
CANMAR DWG. NO B-BOLE-060-02
REV 0


'B'
100
10
75
15
1·5 THK NEOPRENE (OR EQUAL) GASKET OIL & SEA WATER RESISTANT.
DRILLED & TAPPED TO SUIT 1/4" - 27 N.P.T. TERMINAL TUBE
8
8
25
6
'B'

SECTION A~A


50
10
30
10
DRILLED & TAPPED TO SUIT 1/4" I.P.S. TERMINAL TUBE.
8
8
25
COVER PLT.

SECTION B~B


100
10
48
48
8
6
20
20
56
6
10.R.
4-OFF 0·19" DIA HOLES TO SUIT
NOM'L SIZE 10-32 x 2" HEX. HD MACH SCREW, BRASS
'A'
'A'

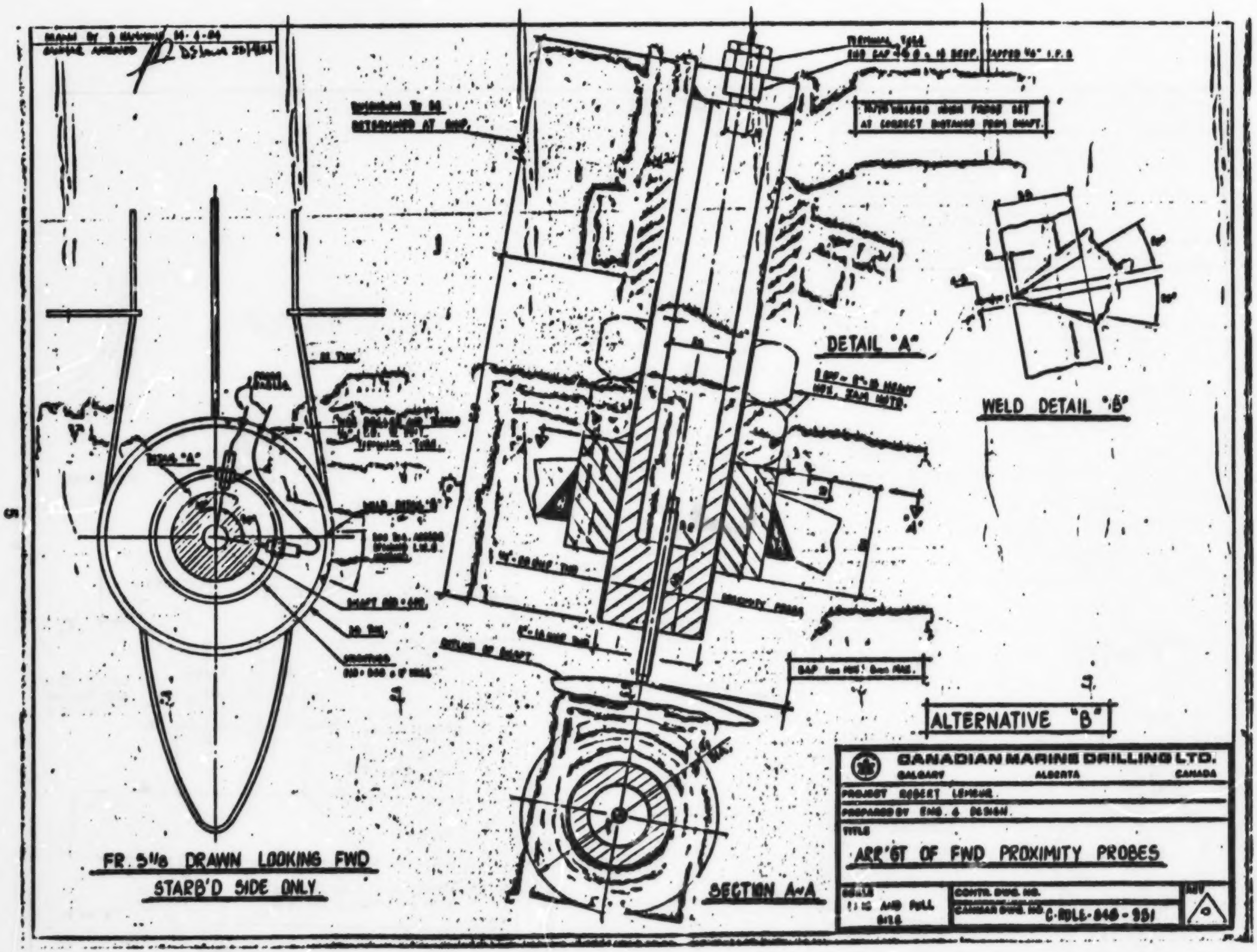
PLAN VIEW

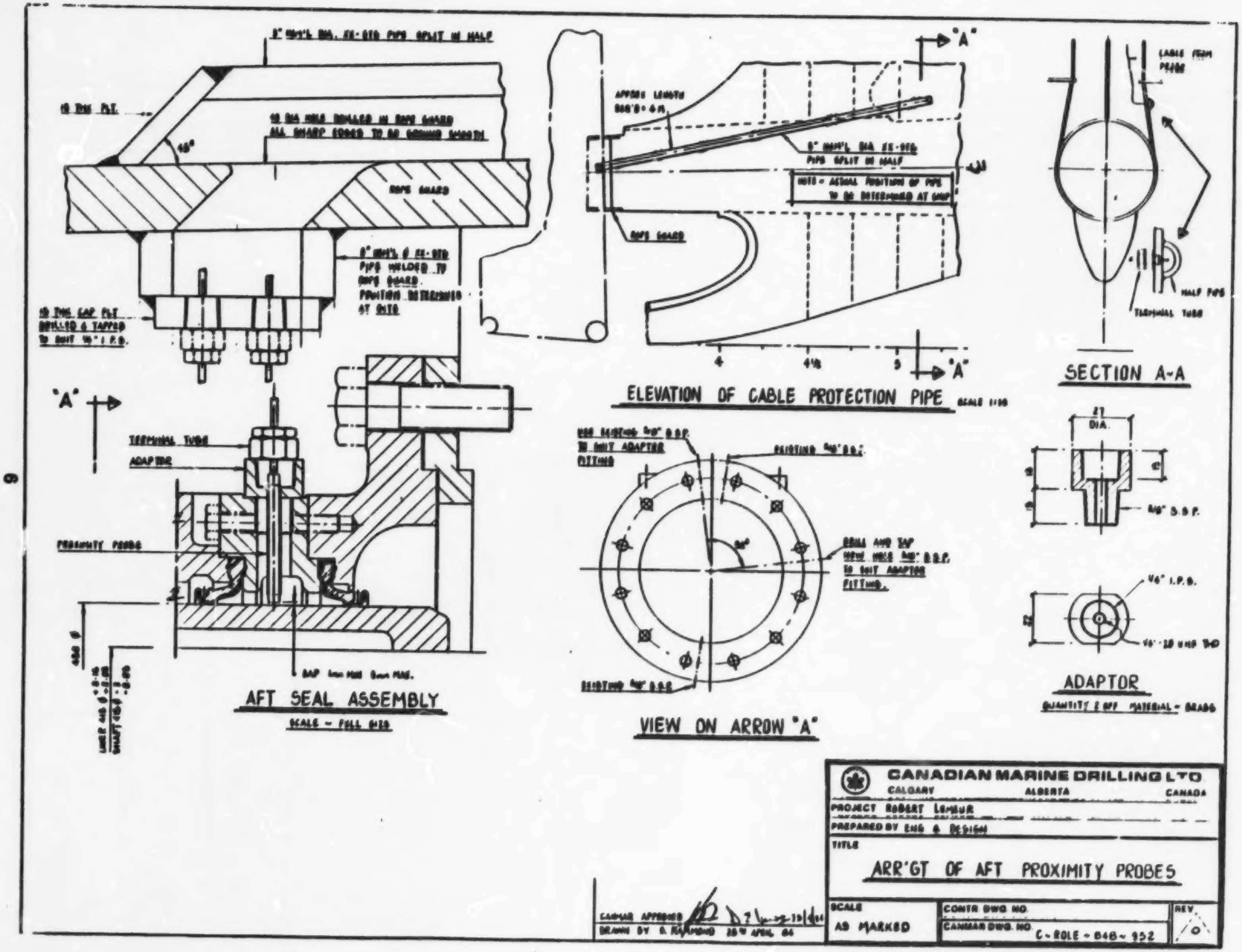
| DESCRIPTION | MATERIAL | QTY |
|---|---|---|
| JUNCTION BOX | BRASS | 1 |
| COVER PLT | D° | 1 |
| NOM'L SIZE 10-32 x 2" HEX. HD MACH SCREWS. | D° | 12 |
| 1·5 THK GASKET | NEOPRENE | 2 |

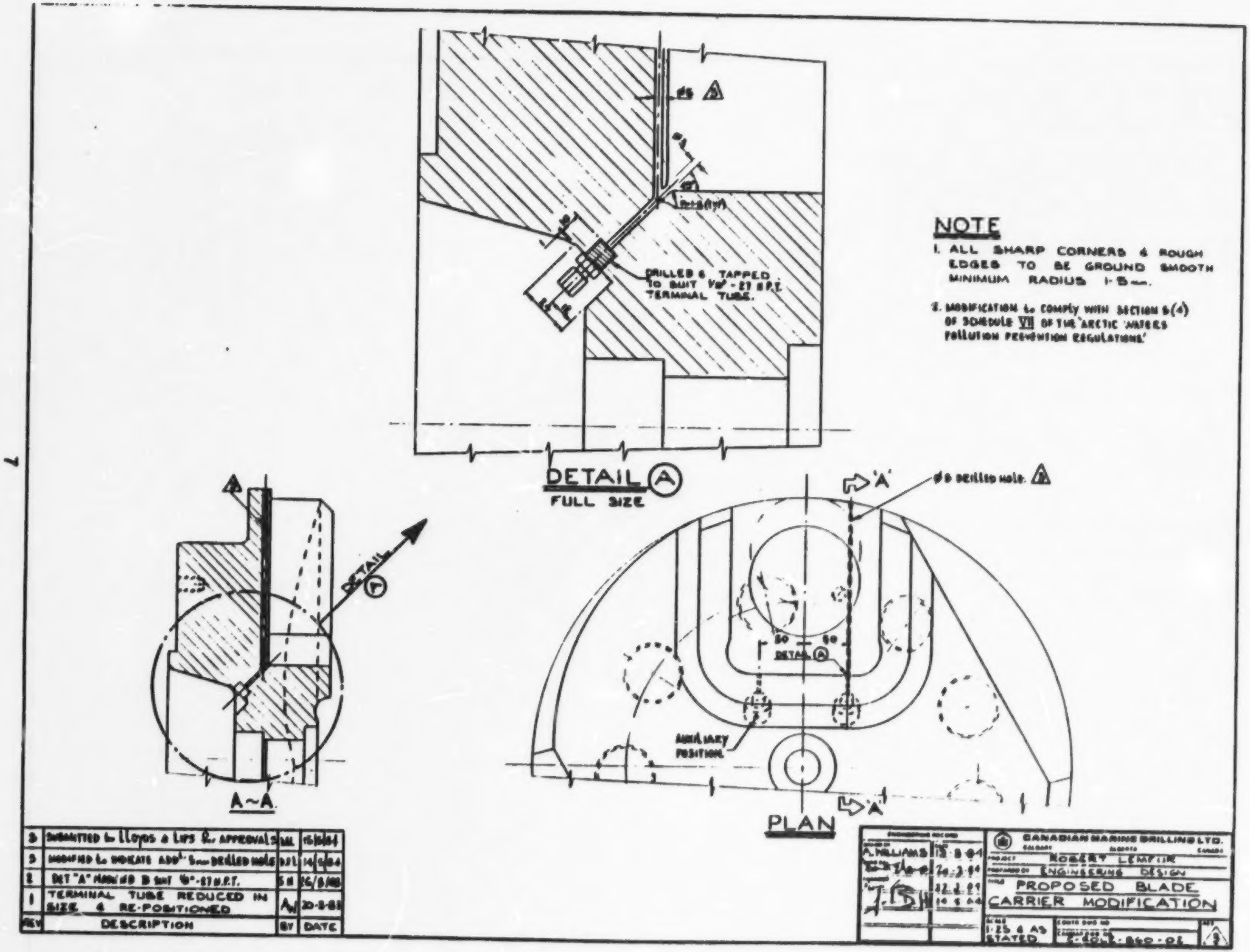
THIS DRG SUPERCEDES DRG # C-ROLE-840-09

| ENGINEERING RECORD | |
|---|---|
| S. HAMMOND | 17th APRIL 84 |
| [illegible] | [illegible] |
| [illegible] | [illegible] |

CANADIAN MARINE DRILLING LTD.
CALGARY ALBERTA CANADA
PROJECT [illegible]
PREPARED BY ENG. & DESIGN
TITLE PROPELLER BLADE TESTS
JUNCTION BOX
SCALE FULL SIZE
CONTR. DWG. NO
CANMAR DWG. NO. B-ROLE-868-01
REV 0


DRAWN BY D. HAMMOND 30-4-84
DESIGN APPROVED D.S. Lowe 20/6/84
DIMENSION TO BE DETERMINED AT SHOP.
TERMINAL TUBE
END CAP 4 Ø x 16 DEEP. TAPPED ⅛" I.P.S.
WELDED WHEN PROBES SET AT CORRECT DISTANCE FROM SHAFT.
DETAIL "A"
WELD DETAIL "B"
SECTION A-A
ALTERNATIVE "B"
FR. 51½ DRAWN LOOKING FWD
STARB'D SIDE ONLY.
CANADIAN MARINE DRILLING LTD.
CALGARY ALBERTA CANADA
PROJECT ROBERT LEMEUR.
PREPARED BY ENG. & DESIGN.
TITLE
ARR'GT OF FWD PROXIMITY PROBES
SCALE 1:10 AND FULL SIZE
CONTR. DWG. NO.
CANMAR DWG. NO. C-RDLL-848-991
REV
0


8" NOM'L DIA. XS-STD PIPE SPLIT IN HALF
10 THK PLT.
45°
10 DIA HOLE DRILLED IN ROPE GUARD
ALL SHARP EDGES TO BE GROUND SMOOTH
ROPE GUARD
8" NOM'L Ø XS-STD
PIPE WELDED TO
ROPE GUARD.
POSITION DETERMINED
AT SITE
10 THK CAP PLT
DRILLED & TAPPED
TO SUIT ½" I.P.S.
"A"
TERMINAL TUBE
ADAPTOR
PROXIMITY PROBE
GAP 1mm MIN 2mm MAX.
LINER 445 Ø
SHAFT 415 Ø
AFT SEAL ASSEMBLY
SCALE – FULL SIZE
APPROX LENGTH
REQ'D = 4 M.
3" NOM'L DIA XS-STD
PIPE SPLIT IN HALF
NOTE – ACTUAL POSITION OF PIPE
TO BE DETERMINED AT SHIP
ROPE GUARD
4
4½
5
"A"
ELEVATION OF CABLE PROTECTION PIPE
SCALE 1:10
CABLE FROM
PROBE
HALF PIPE
TERMINAL TUBE
SECTION A-A
USE EXISTING ⅝" B.S.P.
TO SUIT ADAPTOR
FITTING
EXISTING ⅝" B.S.P.
30°
DRILL AND TAP
NEW HOLE ⅝" B.S.P.
TO SUIT ADAPTOR
FITTING.
EXISTING ⅝" B.S.P.
VIEW ON ARROW "A"
27
DIA.
⅝" B.S.P.
½" I.P.S.
22
ADAPTOR
QUANTITY 2 OFF  MATERIAL – BRASS
CANADIAN MARINE DRILLING LTD
CALGARY  ALBERTA  CANADA
PROJECT ROBERT LEMEUR
PREPARED BY ENG & DESIGN
TITLE
ARR'GT OF AFT PROXIMITY PROBES
SCALE
AS MARKED
CONTR DWG NO.
CANMAR DWG. NO.
C-ROLE-84B-952
REV.
0
CANMAR APPROVED
DRAWN BY D. RAYMOND 26th APRIL 84



DETAIL Ⓐ
FULL SIZE
DRILLED & TAPPED TO SUIT 1/8"-27 N.P.T. TERMINAL TUBE.
ø5
A~A
DETAIL Ⓐ
PLAN
'A'
ø5 DRILLED HOLE.
50
DETAIL Ⓐ
AUXILIARY POSITION

NOTE

1. ALL SHARP CORNERS & ROUGH EDGES TO BE GROUND SMOOTH MINIMUM RADIUS 1·5mm.

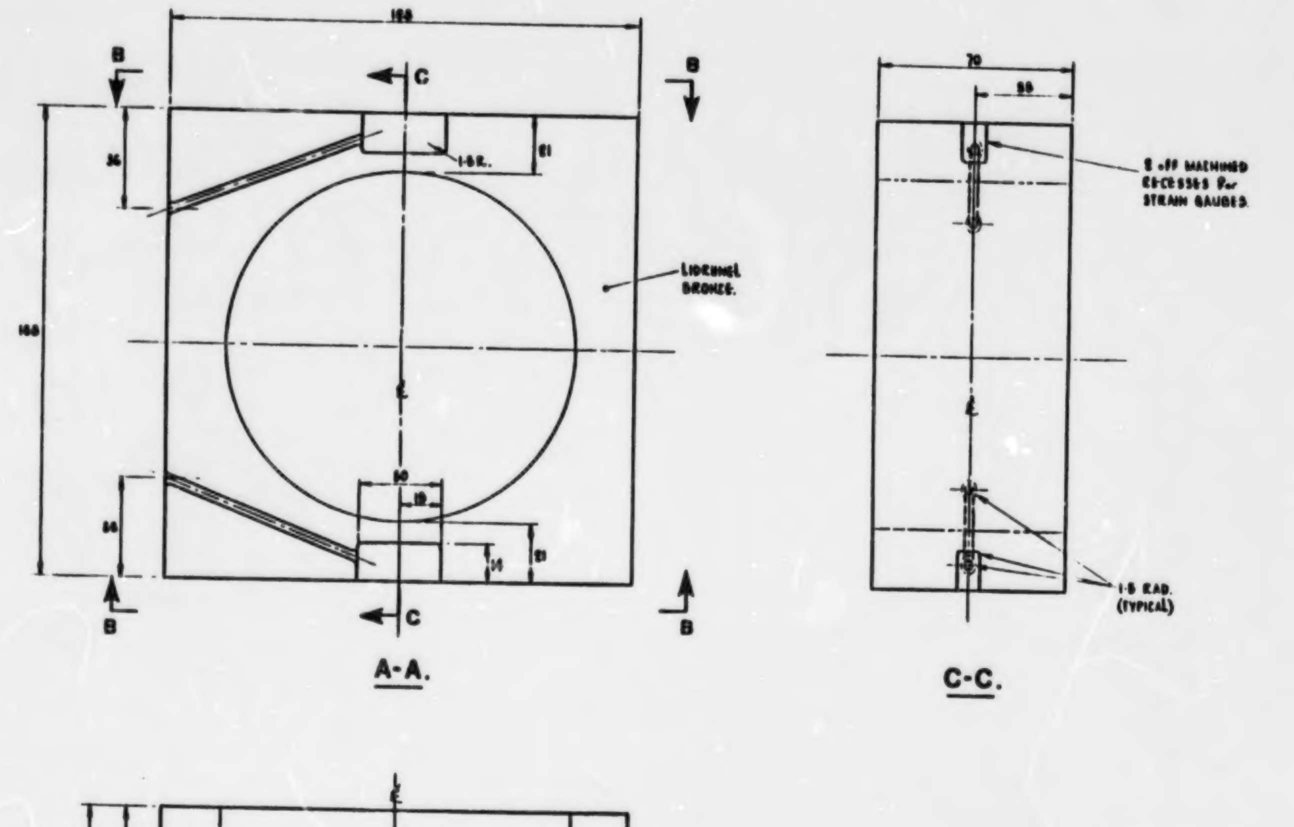
2. MODIFICATION to COMPLY WITH SECTION 5(4) OF SCHEDULE VII OF THE 'ARCTIC WATERS POLLUTION PREVENTION REGULATIONS'

| REV | DESCRIPTION | BY | DATE |
|---|---|---|---|
| 3 | SUBMITTED to Lloyds & Lips for approvals | W.M. | 15/8/84 |
| 3 | MODIFIED to INDICATE ADD'L 5mm DRILLED HOLE | DJL | 14/8/84 |
| 2 | DET "A" MODIFIED to SUIT 1/8"-27 N.P.T. | SH | 26/8/83 |
| 1 | TERMINAL TUBE REDUCED IN SIZE & RE-POSITIONED | AW | 20-8-83 |

CANADIAN MARINE DRILLING LTD.
CALGARY ALBERTA CANADA

PROJECT ROBERT LEMEUR
PREPARED BY ENGINEERING DESIGN
TITLE PROPOSED BLADE CARRIER MODIFICATION
SCALE 1:25 & AS STATED
[illegible]-4043-860-01
REV 3

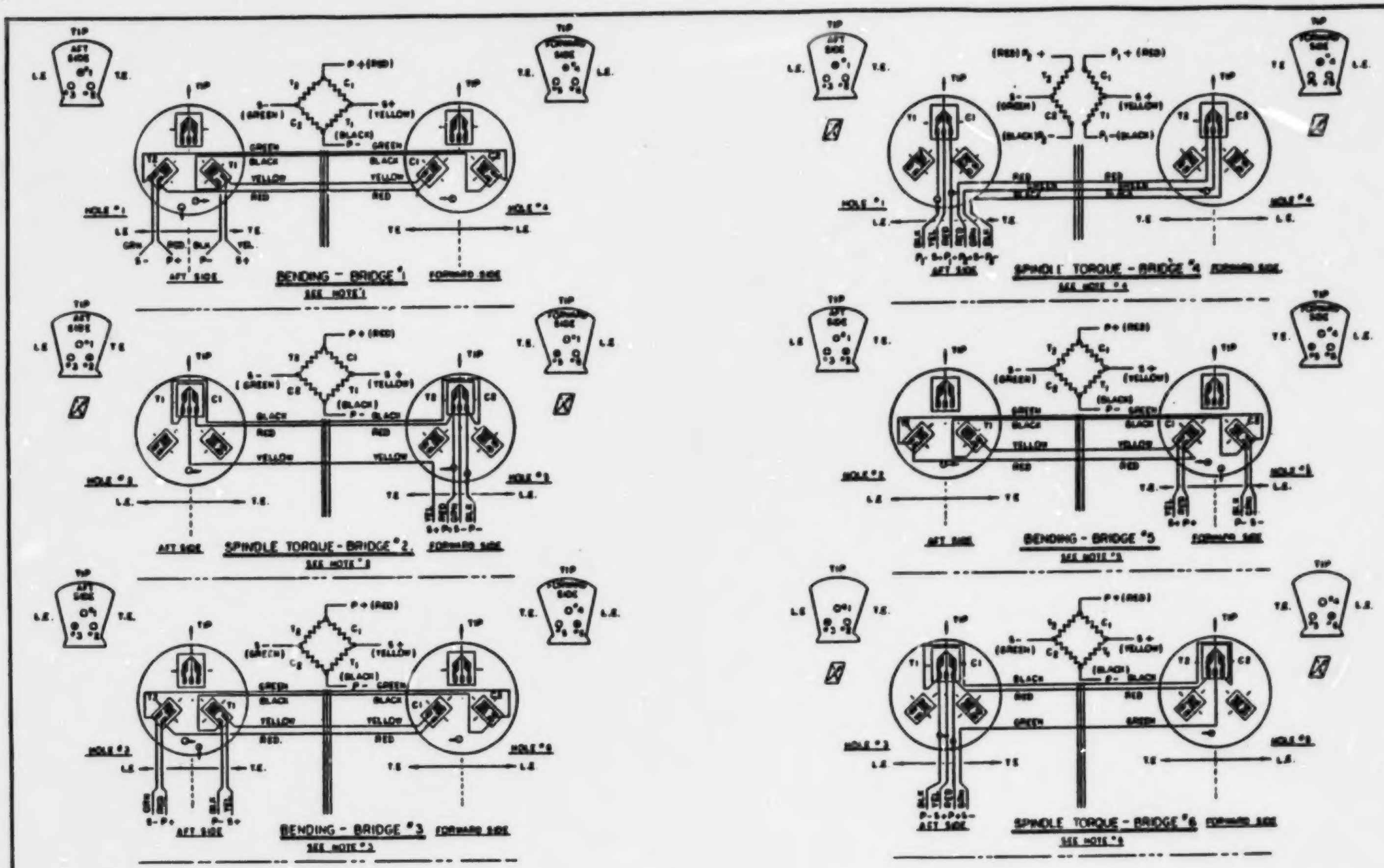
A. WILLIAMS 15-8-84
20-8-84
22-8-84
10-8-84


160
B
C
36
1·6 R.
21
LIDRINEL BRONZE.
160
30
13
36
14
21
A-A.
70
30
2 off MACHINED RECESSES for STRAIN GAUGES.
1·6 RAD. (TYPICAL)
C-C.
30
70
1·6 R.
8.
A
8 DIA DRILLED HOLES.
B-B.

ALL DIMENSIONS in MMs.

| | |
|---|---|
| **CANADIAN MARINE DRILLING LTD.**<br>CALGARY ALBERTA CANADA | |
| PROJECT | ROBERT LEMEUR. |
| PREPARED BY | ENG. & DESIGN. |
| TITLE | SLIDING BLOCK for STBD. C.P. PROPELLER.<br>MACHINING & DRILLING for STRAIN GAUGE INSTRUMENTATION. (PROPOSED) |
| SCALE | FULL SIZE. |
| CONTR. DWG. NO. | — |
| CANMAR DWG. NO. | C-ROLE-8G0-01. |
| REV | 0 |

D.ELONG 1st MAR '84.


TIP
AFT SIDE
FORWARD SIDE
L.E.
T.E.
P+ (RED)
S- (GREEN)
S+ (YELLOW)
(BLACK) P-
GREEN
BLACK
YELLOW
RED
HOLE #1
HOLE #2
HOLE #3
HOLE #4
HOLE #5
HOLE #6
BENDING - BRIDGE #1
SEE NOTE 1
SPINDLE TORQUE - BRIDGE #2
SEE NOTE 2
BENDING - BRIDGE #3
SEE NOTE 3
SPINDLE TORQUE - BRIDGE #4
SEE NOTE 4
BENDING - BRIDGE #5
SEE NOTE 5
SPINDLE TORQUE - BRIDGE #6
SEE NOTE 6
T1
T2
C1
C2

## NOTES

MEASUREMENT OF ICE PROPELLER INTERACTION PARAMETERS

1. BLADE BENDING STRAIN - BRIDGE #1
(POSITIVE BENDING IS TIP BENDING FORWARD)
2. BLADE SPINDLE TORQUE STRAIN - BRIDGE #2
(POSITIVE SPINDLE TORQUE IS TRAILING EDGE TIP BENDING FORWARD)
3. BLADE BENDING STRAIN - BRIDGE #3
(POSITIVE BENDING IS TIP BENDING FORWARD)
4. BLADE SPINDLE TORQUE STRAIN - BRIDGE #4
(POSITIVE SPINDLE TORQUE IS TRAILING EDGE TIP BENDING FORWARD)
5. BLADE BENDING STRAIN - BRIDGE #5
(POSITIVE BENDING IS TIP BENDING FORWARD)
6. BLADE SPINDLE TORQUE STRAIN - BRIDGE #6
(POSITIVE SPINDLE TORQUE IS TRAILING EDGE TIP BENDING FORWARD)

| DRAWING NO. | REFERENCE DRAWINGS | REV | REVISION DESCRIPTION | BY | DATE | CHKD | APP |
|---|---|---|---|---|---|---|---|
| D-ROLE-840-3506 | PROPELLER BLADE STRAIN GAUGE JUNCTION BOX INTER-CONNECTIONS | 0 | ORIGINAL -'AS FITTED' | S.W | 84-05-01 | DGL | JW |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |

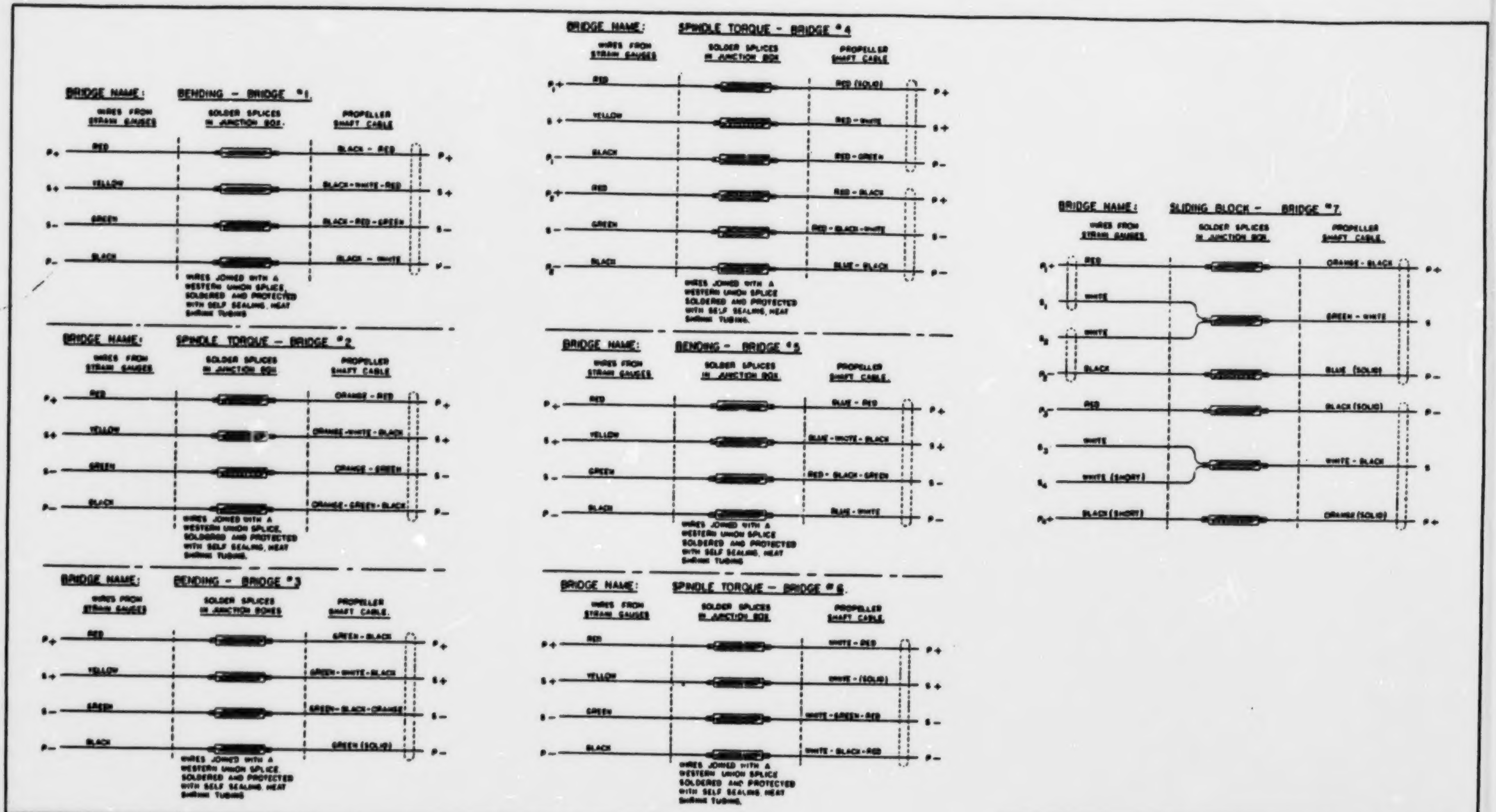
| ENGINEERING RECORD | DATE |
|---|---|
| DRAWN BY<br>S. WILLIAMSON | 84-05-01 |
| CHKD BY | 1st May 84 |
| APPROVED | 84-05-01 |
|  |  |
|  |  |
|  |  |

**CANADIAN MARINE DRILLING LTD.**
CALGARY ALBERTA CANADA

PROJECT ROBERT LE MEUR
PREPARED BY BEAUFORT SEA ENGINEERING & DESIGN

TITLE
PROPELLER BLADE,
STRAIN GAUGE WIRING.

SCALE —
CONTR DWG. NO.
CANMAR DWG. NO. D-ROLE-840-3505
REV 0


BRIDGE NAME: BENDING - BRIDGE #1.
WIRES FROM STRAIN GAUGES
SOLDER SPLICES IN JUNCTION BOX.
PROPELLER SHAFT CABLE
P+
RED
BLACK - RED
P+
S+
YELLOW
BLACK-WHITE-RED
S+
S-
GREEN
BLACK-RED-GREEN
S-
P-
BLACK
BLACK - WHITE
P-
WIRES JOINED WITH A WESTERN UNION SPLICE, SOLDERED AND PROTECTED WITH SELF SEALING, HEAT SHRINK TUBING
BRIDGE NAME: SPINDLE TORQUE - BRIDGE #2
WIRES FROM STRAIN GAUGES
SOLDER SPLICES IN JUNCTION BOX
PROPELLER SHAFT CABLE
P+
RED
ORANGE - RED
P+
S+
YELLOW
ORANGE-WHITE-BLACK
S+
S-
GREEN
ORANGE - GREEN
S-
P-
BLACK
ORANGE-GREEN-BLACK
P-
WIRES JOINED WITH A WESTERN UNION SPLICE, SOLDERED AND PROTECTED WITH SELF SEALING, HEAT SHRINK TUBING.
BRIDGE NAME: BENDING - BRIDGE #3
WIRES FROM STRAIN GAUGES
SOLDER SPLICES IN JUNCTION BOXES
PROPELLER SHAFT CABLE.
P+
RED
GREEN - BLACK
P+
S+
YELLOW
GREEN-WHITE-BLACK
S+
S-
GREEN
GREEN-BLACK-ORANGE
S-
P-
BLACK
GREEN (SOLID)
P-
WIRES JOINED WITH A WESTERN UNION SPLICE. SOLDERED AND PROTECTED WITH SELF SEALING HEAT SHRINK TUBING
BRIDGE NAME: SPINDLE TORQUE - BRIDGE #4
WIRES FROM STRAIN GAUGES
SOLDER SPLICES IN JUNCTION BOX
PROPELLER SHAFT CABLE
P1+
RED
RED (SOLID)
P+
S+
YELLOW
RED - WHITE
S+
P1-
BLACK
RED - GREEN
P-
P2+
RED
RED - BLACK
P+
S-
GREEN
RED - BLACK - WHITE
S-
P2-
BLACK
BLUE - BLACK
P-
WIRES JOINED WITH A WESTERN UNION SPLICE SOLDERED AND PROTECTED WITH SELF SEALING, HEAT SHRINK TUBING.
BRIDGE NAME: BENDING - BRIDGE #5
WIRES FROM STRAIN GAUGES
SOLDER SPLICES IN JUNCTION BOX.
PROPELLER SHAFT CABLE.
P+
RED
BLUE - RED
P+
S+
YELLOW
BLUE - WHITE - BLACK
S+
S-
GREEN
RED - BLACK - GREEN
S-
P-
BLACK
BLUE - WHITE
P-
WIRES JOINED WITH A WESTERN UNION SPLICE SOLDERED AND PROTECTED WITH SELF SEALING, HEAT SHRINK TUBING
BRIDGE NAME: SPINDLE TORQUE - BRIDGE #6.
WIRES FROM STRAIN GAUGES
SOLDER SPLICES IN JUNCTION BOX
PROPELLER SHAFT CABLE
P+
RED
WHITE - RED
P+
S+
YELLOW
WHITE - (SOLID)
S+
S-
GREEN
WHITE - GREEN - RED
S-
P-
BLACK
WHITE - BLACK - RED
P-
WIRES JOINED WITH A WESTERN UNION SPLICE SOLDERED AND PROTECTED WITH SELF SEALING HEAT SHRINK TUBING.
BRIDGE NAME: SLIDING BLOCK - BRIDGE #7.
WIRES FROM STRAIN GAUGES
SOLDER SPLICES IN JUNCTION BOX.
PROPELLER SHAFT CABLE.
P1+
RED
ORANGE - BLACK
P+
S1
WHITE
GREEN - WHITE
S
S2
WHITE
P2-
BLACK
BLUE (SOLID)
P-
P3-
RED
BLACK (SOLID)
P-
S3
WHITE
WHITE - BLACK
S
S4
WHITE (SHORT)
P4+
BLACK (SHORT)
ORANGE (SOLID)
P+

| DRAWING NO. | REFERENCE DRAWINGS | REV. | REVISION DESCRIPTION | BY | DATE | CHKD | APP |
|---|---|---|---|---|---|---|---|
| D-ROLE-840-3505 | PROPELLER BLADE STRAIN GAUGE WIRING. | 0 | ORIGINAL - 'AS FITTED' | R.W. | 84-06-13 | B | AH |
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| ENGINEERING RECORD | |
|---|---|
| DRAWN BY<br>R. WILLIAMSON | DATE<br>84-06-13 |
| CHKD BY | 84-06-13 |
| ENGINEER | 84-06-13 |
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**CANADIAN MARINE DRILLING LTD.**
CALGARY ALBERTA CANADA

PROJECT ROBERT LE MEUR

PREPARED BY BEAUFORT SEA ENGINEERING & DESIGN

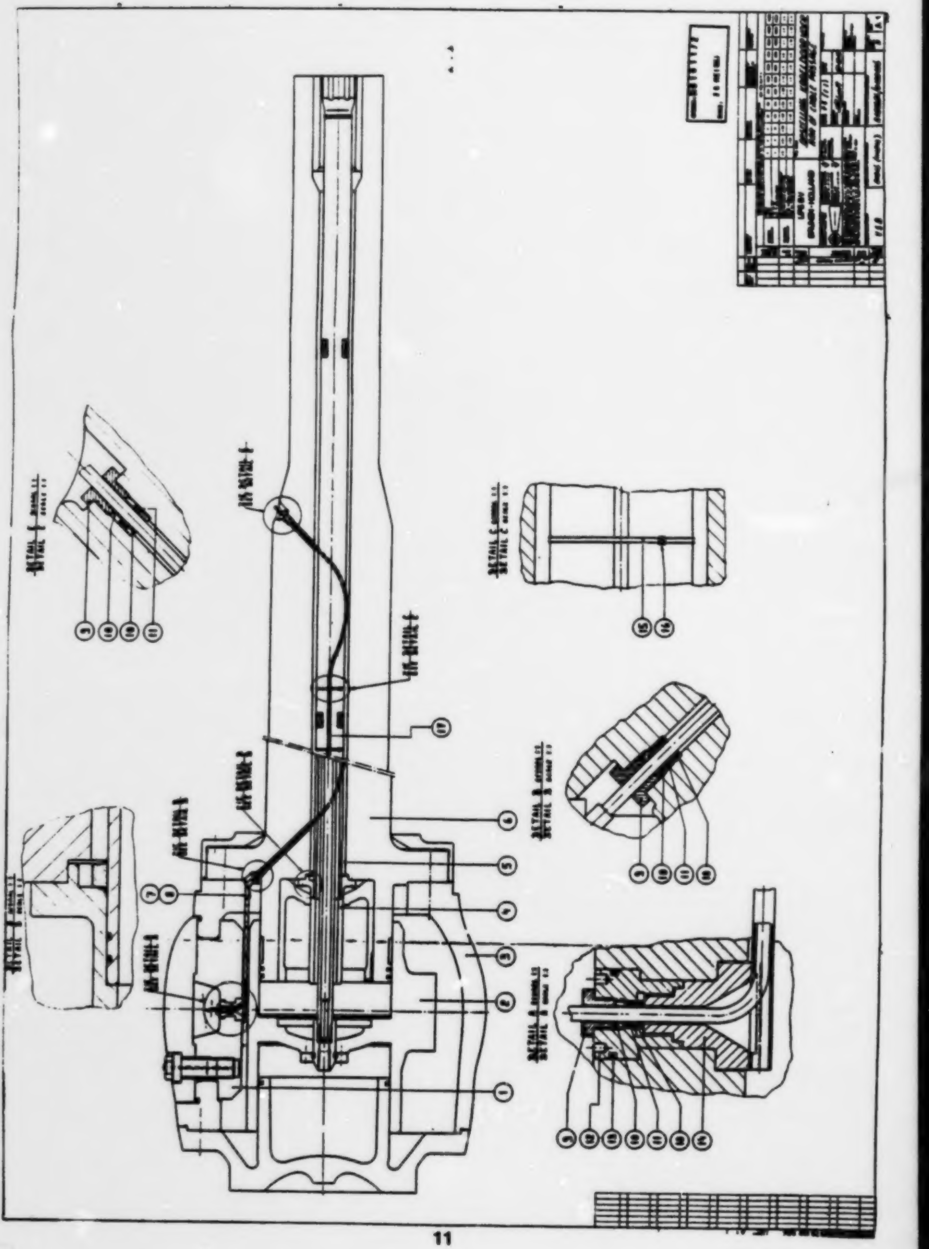
TITLE
PROPELLER BLADE STRAIN GUAGE
JUNCTION BOX INTER-CONNECTIONS

SCALE —

CONTR. DWG. NO.

CANMAR DWG. NO. D-ROLE-840-3506

REV 0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